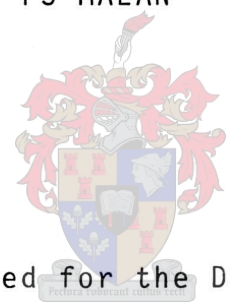
STUDIES ON THE PHENOTYPIC VARIATION IN GROWTH STRESS INTENSITY AND ITS ASSOCIATION WITH TREE AND WOOD PROPERTIES OF SOUTH AFRICAN GROWN *EUCALYPTUS GRANDIS* (HILL EX MAIDEN)

BY

FS MALAN



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Promotor: Prof GFR Gerischer

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ABSTRACT

The level of growth stress in the stems of *Eucalyptus grandis* trees is apparently not determined by environmental factors to any great extent. A significant positive relationship was found between level of growth stress and rate of growth, but the latter accounted for only a small proportion of the enormous variation that characteristically exists among plantation grown trees. It may, however, explain to some extent why trees on poor quality sites tend to develop less end-splitting in their logs as compared to those from better quality sites.

Seasonal fluctuations in the level of growth stress were observed. Attempts to explain these fluctuations in terms of weather patterns and soil moisture content yielded contradictory results. Although not quantitatively proved, there was some evidence to suggest that the level of growth stress is intensified in actively growing trees during periods of severe soil moisture deficit.

Studies on open- and control-pollinated material indicated a very definite genetic variation among families. A narrow-sense heritability estimate of 0,56 was obtained. The genetic manipulation of growth stress therefore seems to constitute the most promising means of growth stress reduction in trees of this species, and it can be done irrespective of tree characteristics. Since a poor relationship was found between growth stress intensity and rate of growth, the selection for reduced level of growth stress and increased volume growth can be employed simultaneously.

Marked differences in a number of anatomical features and wood density were found among trees of widely different growth stress intensities. Results suggested that the genetic

reduction of the level of growth stress in a tree improvement programme would result in a reduction in the pith-to-bark wood density and fibre length gradients, causing lower values in the outer parts of the stem for both these properties. Since these properties are the most widely used indices for wood quality, this implies that the selection for reduced level of growth stress would, apart for a reduction in splitting, result in reduced within-tree variability in wood quality.

Furthermore, the observed differences in anatomical characteristics between trees of different levels of growth stress suggest that anatomical determinations could be used as an effective means to separate low-stressed trees from high-stressed trees. Results indicated that the inherent potential of a tree to generate growth stress of a particular level may even be assessed at a fairly young age from the anatomical characteristics of the wood. However, further research is needed to quantify this in more exact terms before they can be used for predicting level of growth stress with sufficient precision.

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PART I

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CHAPTER ONE

INTRODUCTION

1.1 Hardwood afforestation in South Africa.

South Africa is relatively poorly endowed with natural forests. Indigenous forests cover only about 0,25 per cent of the total land surface, which is an almost negligible area when compared to the natural timber resources of many other countries, especially those in the Northern hemisphere. Indigenous forests are mainly managed by the Directorate of Forestry of the Department of Environmental Affairs as protected areas to preserve its beauty and to protect it from injudicious exploitation. Only a small amount of timber (between 5 000 and 10 000 cubic metre) is produced annually and is usually sold on tender (Lubbe, 1980). The country is, therefore, forced to rely heavily on imported timber and timber obtained from locally grown exotic soft- and hardwood plantations to provide in her timber needs.

Softwood afforestation is based predominantly on various Pine species. These are managed to yield sawlogs for the production of structural, industrial and other sawn timber, veneer logs, poles, and raw material for the pulp, paper and board industries. Due to an intensive afforestation programme of the last few decades, the country has become virtually self-sufficient as regards softwood timber.

Eucalyptus species serve as the most important local source of hardwood timber. Several species are planted on a commercial basis and are utilized for a variety of purposes. In total, commercial Eucalypt plantations embrace about 72 per cent of the total hardwood afforested area. The rest of the area consists of Wattle plantations, managed to produce wattle bark, mining timber, pulp wood and fire wood; and small areas of Poplar, grown almost exclusively for the production of matches.

The major Eucalypt species grown commercially in South Africa are *E. grandis*, *E. cloeziana*, *E. diversicolor*, *E. fastigata*, *E. paniculata* and *E. maculata*. The bulk of the Eucalypt plantations (88 per cent) are privately owned while the rest are publicly owned. Among the various Eucalypt species planted in South Africa, *Eucalyptus grandis* is by far the most important and is gaining in popularity (Table 1.1). This is mainly due to its adaptability to South African conditions, excellent stem form, good branch properties, rapid growth, freeness from pests and diseases, ease of cultivation, and the fact that it produces a highly versatile, general-purpose timber. At present it covers about 80 per cent of established Eucalypt plantations. Until recently it has been confused with *Eucalyptus saligna* and, as a result, it is still referred to as "saligna" in the timber trade.

Since the introduction of this species in South Africa, and particularly during the post-war period, the importance of this species increased rapidly, not only as a mining and pulpwood timber, but also as a saw timber and for many other purposes. Between 1945 and 1960 the area under *Eucalyptus grandis* increased by 300 per cent to a total area of about 112 500 hectares (Luckhoff, 1967). By 1969/70 the afforested area has increased to 242 091 hectares. Since then the area under *Eucalyptus grandis* increased steadily to an area presently estimated at just over 300 000 hectares. This is the largest afforested area of this species in one country outside Australia. In view of all this it can be expected that this species will play an increasingly important economic role in the future expansion of the country's hardwood timber industry.

Eucalyptus grandis is grown on a short rotation of 6 to 10 years for the production of mining timber, pulpwood, building poles, fencing materials and firewood, on a medium rotation of 10 to 14 years for the production of telephone and transmission poles, and on a moderately long rotation of 14 to 38 years for the production of sawlogs, veneerlogs and harbour piles.

1.2 Consumers of hardwood in South Africa.

At present the mining and pulp industries are the largest consumers of locally produced hardwoods. Together they are responsible for more than 88 per cent of the total annual consumption by primary processing industries (Table 1.2). The sawmilling industry is the third largest consumer of hardwoods, followed by the pole industry, but by comparison the intakes of these industries are relatively small.

The annual intake of *Eucalyptus grandis* increased in all four major product categories in recent years. The total annual intake of the four categories changed between 1969/70 to 1981/82 as follows (Lubbe, 1980):

	1969/70 (m^3)	1981/82 (m^3)	Percentage change
Eucalyptus grandis	2733	5062	+ 85,2
Other Eucalypts	606	1013	+ 67,2
Wattle	1436	1057	- 26,4
Other hardwoods	33	49	+ 47,3

A recent survey (Lubbe, 1980) indicated that the demand for mining timber fluctuated around an average of about 1,9 million tons per annum for the last number of years. However, the composition of species changed dramatically since 1969. The intake of *Eucalyptus grandis* increased by about 54 per cent while the intake of other gums showed an increase of 33 per cent. Wattle intake, on the other hand, declined by 77 per cent in the same period.

It is expected that the annual intake of mining timber will start to decline after 1990 as a result of the growing tendency to replace timber by non-timber prop types. Timber is no longer considered an adequate support material in modern mining operations because it does not provide adequate initial support,

because of its variability in yield/strength characteristics, and the fear of underground fires. It can be expected that these developments would lead to a reduction in the area allocated for mining timber production, resulting in an increase in supply of timber available for other purposes.

TABLE 1.1: Hardwood plantation areas according to management aims (per cent of total hardwood afforested area) (1977/78)

Commodity	Area (per cent)
Sawlogs:	
Eucalyptus grandis	6,05
Other Eucalypts	2,20
Wattle	0,71
Poles:	
Eucalyptus grandis	4,15
Other Eucalypts	2,22
Wattle	0,81
Mining timber:	
Eucalyptus grandis	24,86
Other Eucalyptus	7,20
Wattle	7,43
Pulpwood:	
Eucalyptus grandis	21,62
Other Eycalypts	2,05
Wattle	13,72
Other:	
Eucalyptus grandis	0,58
Other Eucalypts	1,53
Wattle	4,87
Total:	
Eucalyptus grandis	57,26
Other Eucalypts	15,20
Wattle	27,54

The pulpwood market maintained an annual growth of more than 10 per cent since 1979 (Lubbe, 1980). Species composition as regards hardwood intake remained more or less the same, i.e. *Eucalyptus grandis* 63 per cent, other Eucalypts 5 per cent, and Wattle 32 per cent.

TABLE 1.2: Annual consumption of hardwood roundwood by primary processing industries (per cent of total intake)(1977/78)

	E. grandis	Other Eucalypts	Wattle	Other hardwoods	Total
Sawlogs	5,49	1,72	-	0,09	7,30
Mining timber	32,02	8,44	4,54	-	45,00
Pulpwood	3,25	0,27	0,37	-	3,90
Veneer	-	-	-	0,40	0,40
Matchwood	-	-	-	0,40	0,40

The intake of hardwood sawlogs for the production of structural and industrial timber showed only a slight growth during 1968/70 (Lubbe, 1980). However, *Eucalyptus grandis* has shown an increase of 40 per cent in the same period. At present about 98 per cent of the total hardwood sawlog intake consists of Eucalypts of which *Eucalyptus grandis* shares about 75 per cent.

The pole market showed an average annual growth of 6,4 per cent during 1969 to 1978. Only *Eucalyptus grandis* and Wattle showed signs of growth while the use of other Eucalypts declined markedly during this period.

1.3 Hardwood import replacement.

Although local hardwoods provide adequately for many uses, it is considered unsuitable for some specialized purposes, mainly as a result of the problems arising from the presence of high levels of growth stress. These stresses cause the development of radial splits in log ends during and after logmaking. Due to the release of residual stresses in the log during sawing, further distortion takes place causing additional splitting. Such distortion occur as spring in radial-sawn boards and as bow in flat-sawn boards and is accentuated during seasoning. As a result of this, and the fact that material of thicker dimensions are difficult to season, sawmillers prefer not to produce Eucalypts boards thicker than 25mm and wider than 175mm. This of course limits the market range even for acceptable boards (Lubbe, 1980).

At present local production provides in about 99 per cent of the hardwood sawlog and pole consumption, 52 per cent of the sawn timber consumption, 17 per cent of the sleeper consumption, and 53 per cent of the ceiling and flooring consumption (Lubbe, 1980). South Africa is, therefore, forced to import a considerable volume of hardwood timber to meet the requirements for furniture, joinery, veneer, railway sleepers, and other specialized purposes where high quality and large dimensions are essential. The bulk of the timber imported into the country is used in the furniture and joinery industries. Since 1970 between 50 and 60 per cent of the total hardwood imports were consumed by these sectors of the timber industry.

As a result of an ever increasing world-wide demand for hardwood timber, and the resultant increase in cost of imported timber, South Africa will have to rely more and more on local sources to provide in the future needs of the

country. To meet this demand, an increase in local production, a considerable improvement in timber quality and the finding of suitable substitutes for the wide range of special uses presently met by imported timber, will be essential.

Studies indicated that a large proportion of imported timber for veneer and sleeper production and for joinery purposes can be replaced by locally grown timbers, provided present quality problems can be overcome (Lubbe, 1980; van der Westhuizen, 1978; Margadant, 1981).

In 1979 the joinery and furniture industries imported 58 per cent of their total consumption. Although many of the timbers imported by these industries can potentially be replaced by locally produced timbers, they are reluctant to do so because of consumer preference for specific timber species, the non-availability of thick dimension material, variability in quality, and the presence of seasoning defects (van der Westhuizen, 1978).

Furniture made from imported timbers such as Imbuia, kiaat, Iroko, Ash, Pau Marfim, and others, cannot be replaced by locally grown hardwoods. Furniture manufactured from these timbers is already in the expensive range and will get more and more expensive and beyond the financial reach of an increasing proportion of the population. As a result of this, it can be expected that the future market prospects for locally grown hard- and softwoods for use in the furniture industry for cheaper types of furniture will continue to grow, provided existing quality problems can be overcome.

Recent developments in the manufacture of laminated railway sleepers from locally produced pine timber have lead to a considerable reduction in sleeper imports. It is expected that the use of these sleepers will result in an annual saving

of at least R9 000 000 in foreign currency (Kromhout, 1983; Krogh, 1982). Locally produced hardwood could also enter this market provided the serious splitting problems and difficulty of treating these timbers with preservatives can be solved.

The hardwood veneer industry relies almost entirely on imported veneer logs. Recent studies by Margadant (1981) indicated that a number of local Eucalypts, including *Eucalyptus grandis*, produce excellent veneer material but yields are low as result of severe end-splitting. Problems associated with high levels of growth stresses can be controlled to some extent if end-splitting can be restrained effectively until logs are conditioned for peeling, for instance by circumferential grooving (see: Malan, 1979a; Conradie, 1980; Barnacle, 1978). The plasticizing effect caused by the high temperature and wet conditions appears to relieve some of the stresses, resulting in a significant improvement in veneer yield.

1.4 Research requirements

The present thinking of using locally grown hardwoods will lead to an increased demand in high quality timber. To meet this demand an increase in the hardwood afforested area, among other things, will be essential. However present estimates indicate that the existing plantation area will have to be doubled by the year 2000 to meet South Africa's growing demand for soft- and hardwoods. This would mean an annual afforested rate of roughly 50 000 hectares. In view of the fact that only about 8 per cent of the land surface is suitable for afforestation, this would mean that within a few decades no land would be available for further afforestation. Various research projects are at present conducted towards increasing production per unit area through tree breeding, choice of more suitable species, improved silvicultural techniques and the use of inorganic fertilizers.

To satisfy existing and future demands for locally produced high quality timber, considerable research should also be directed towards increasing the profitability and productivity of the hardwood processing industry. There can be no doubt that the presence of high levels of growth stresses, a prominant feature in most South African grown Eucalypts, is one of the most important defects in terms of its effect on conversion efficiency, product quality and sawn dimensions.

Various studies have been undertaken in order to control splitting in logs prior to conversion or to provide sawmillers with measures to obtain maximum recovery and quality from highly stressed Eucalypt logs. Unfortunately these measures have met with limited success. Unless sawmillers can be supplied with logs free of serious splitting, losses due to end-splitting will remain substantial. The ultimate solution therefore lies in the growing of trees containing stress levels low enough not to cause any severe utilization problems.

An enormous variation in log end-splitting characteristically exists among Eucalypts trees, even between trees growing apparently under uniform conditions. This suggests that the level of growth stress in a tree is either controlled by micro-environmental or by genetic factors or a combination of the two. In other words, the manipulation of stress levels by genetic and/or environmental means seems to be feasible.

No known attempt has yet been made to explain the variation in log end-splitting among *Eucalyptus grandis* trees in terms of genetic and environmental influences. Because of the importance of such information in a tree improvement programme, this investigation was undertaken to establish more precisely the extent this variation is controlled by environmental and genetic factors.

Previous studies revealed a definite association between stress levels and wood properties within trees (Nicholson *et al.*, 1972, 1973a), but no known attempt has been made to relate between-tree differences in stress levels to differences in wood properties. Such information is of vital importance and would help to explain the wide variation in wood properties often observed between trees of this species. More important, however, it would indicate to what extent wood properties will be affected as a result of the manipulation of the level of stress in individual trees. It might also provide more easily assessed features which could be utilized to assess levels of stress in standing trees in a fast and non-destructive way.

Although growth stresses occur in all South African grown Eucalypts with varying degrees of severity, it is particularly severe in *Eucalyptus grandis*. For this reason, and due to the economic importance of this species, this study will be confined to *Eucalyptus grandis* growing in the North-Eastern Transvaal region. It can be assumed, however, that the findings of this study may apply to a large extent to all South African Eucalypts.

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CHAPTER TWO

THE SPECIES

2.1. Natural occurrence

Eucalyptus grandis (Rose gum or Flooded gum) occurs in the coastal belt between Newcastle in New South Wales and the Brisbane-Maryborough region of Eastern Queensland in Australia. Further North, near Mackay and the Atherton Tableland it is found in isolated localities. Latitudinally the range extends from approximately 17 to 33°S. It is found from sea level to 300m in the South, but in the North it occurs at altitudes of up to 900m (Poynton, 1979).

The climate is mainly subtropical to warmer temperate. The humidity is high throughout the year. Frost does occur occasionally at the higher altitudes and in the valleys. The mean annual rainfall is between 1 000 and 1 800mm, occurring mostly during summer. The mean monthly rainfall during the dry season rarely amounts to less than about 25mm (Streets, 1962; Poynton, 1979).

The tree grows on flats and lower slopes of deep fertile valleys in the Southern parts of its range. In the Northern ascends to tablelands it grows mostly in deep moist but well-drained loams of alluvial or volcanic origin (Streets, 1962; Poynton, 1979).

2.2. Characteristics and uses in Australia

In Australia *Eucalyptus grandis* quite often reaches a height of 40 to 55m and a diameter of 1200 to 1800mm. The bole

is characteristically well shaped and free of branches for nearly two-thirds of its total height. It has a spreading, rather open crown (Streets, 1962; Poynton, 1979).

The tree produces wood which is lighter, softer, less durable and more fissile than most Eucalypt species. The wood tends to warp easily and to develop other defects during seasoning, particularly when sawn from fast-grown trees. The wood shrinks relatively little during seasoning.

The colour of the wood is pink or pale red to reddish-brown, has a straight grain and open texture. It has a mean density of 0,81g.cm^{-3} air-dry and is fairly strong, tough and hard in relation to its mass. The wood is not very durable in contact with the ground, but it is very seldom attacked by Lyctus beetles (Poynton, 1979).

Eucalyptus grandis is one of the less important trees in Australia from an economic point of view. This is in contrast with many other countries where this species is considered as a major exotic species and used for many purposes. In Australia *Eucalyptus grandis* is mainly used for house construction, weather-boarding, flooring and general carpentry (Poynton, 1979). Immature trees are sawn for fruit cases (WRI, 1972).

2.3 Historical background in South Africa

All Eucalypts in South Africa are commonly known as "blue gum". This name was given to the first Eucalyptus species that was introduced into South Africa in 1828, namely *Eucalyptus globulus*, due to the bluish appearance of its bark and leaves. Today this name is indiscriminately used for all South African grown Eucalypts (Forestry Council, 1978).

Since the introduction of *Eucalyptus globulus* in South Africa, more than 150 other Eucalyptus species have been tested in this country. Today many species such as *Eucalyptus ficifolia*, *Eucalyptus gomphocephala*, *Eucalyptus cladocalyx* and *Eucalyptus camaldulensis* are planted mainly for ornamental purposes, for sand fixation, as shelter belts, and for the production of firewood. Tests carried out on material from arboreta and plantations located in most of our climatic regions have revealed that, with certain reservations, species like *E. grandis*, *E. saligna*, *E. microcorys*, *E. maculata*, *E. citriodora*, *E. diversicolor*, *E. fastigata*, *E. muelleriana*, *E. obligua*, *E. oreades*, *E. globoidea*, *E. fraxinoides*, *E. quadrangulata* and *E. resinifera* are suitable for the production of sawn timber and some of them for pulp production (De Villiers, 1973).

Eucalyptus grandis was first introduced into South Africa late in the nineteenth century under the name of *Eucalyptus saligna*. At that stage the two taxa had not been regarded as two distinct species. In 1902 Baker and Smith described *E. grandis* as a variety of *E. saligna*. Although Hill proposed the name *E. grandis* for Rose or Flooded gum in 1862, it was only between 1902 and 1929, after research by Maiden, that the tree was accepted as a separate species under the name *E. grandis*. Only since 1939 seed started entering the country under the name *E. grandis*. Before that time quite a number of seed consignments were received in South Africa from Australia under the name *E. saligna*. As a result of this, *E. grandis* is still commonly known as "saligna" in South Africa.

Since the introduction of *E. grandis* and *E. saligna*, several provenance trials were established in several areas in South Africa, not only to test the performance of the two species, but also to test the performance of seed from different origins in Australia. In general, *E. grandis* proved to be a much faster growing tree than *E. saligna* and exhibits a much better stem form.

In 1961 a comprehensive tree breeding programme for *E. grandis* was started by the Department of Forestry at the J.D.M. Keet Forest Research Station (formerly known as the Zomerkomst Tree Breeding Station). Today two clonal seed orchards are in existence producing about 6 300kg of capsules annually (van Wyk, 1980).

Eucalyptus grandis has proved to be one of the most successful exotic trees. To date a total area of more than 500 000ha has been afforested with it outside Australia, of which more than half exists in South Africa. In Southern Africa this species is grown on a much larger scale than any other Eucalypt. It is planted on a fairly large scale in Angola, Malawi, Zimbabwe, Zambia and especially South Africa. It is also planted on a small scale in South West Africa, Mocambique and Botswana (Poynton, 1979).

2.4 The tree and its wood characteristics

Eucalyptus grandis characteristically shows an extremely good form. It grows very fast under favourable conditions and can reach a height of up to 72m. In well managed stands it develops a slender, lofty, branchless shaft-like bole, which can rise to a height of 24m in mature trees. The tree develops moderately light branches. It is also characterised by its smooth, greenish-white bark (Forestry Council, 1978).

The tree grows extremely fast, especially in young stands. A mean annual height increment of up to 3m has been experienced on good sites in the first ten years of growth. A high volume increment is usually maintained on good sites for many decades although the mean annual increment culminates at the age of 10 to 13 years in the Transvaal and 10 to 17 years in Zululand (van Laar, 1961; Schönau, 1974 as reported by Poynton, 1979).

Eucalyptus grandis is comparatively free from fungal and insect attacks. Although a few incidents have been reported since the species has been introduced, they were never considered as serious (Poynton, 1979).

Eucalyptus grandis grows the best in a warm, humid climate and has therefore been used most extensively for afforestation in silvicultural zones B2 to B4. It is also grown in the warmest parts of zone B5 and in the most humid parts of zones C2 to C5. It has been planted experimentally in zones B3 to B4 in the winter rainfall areas with good results (Poynton, 1979).

The colour of the wood varies from greyish to yellowish-white through all shades of pink to dark red. The wood has a tendency to become reddish-brown to brown on exposure or if oiled. The grain is usually straight and the texture fairly even, though open and slightly coarse. As a result of colour and density variations within the growth rings, wood from older trees often displays an attractive wavy or mahogany-like, ribbon figure when quarter sawn. Interlocked or wild grain sometimes occurs in the outer rings of trees older than 40 years.

The wood is diffuse porous and the growth rings are not very distinct. Vessels are oval shaped, solitary and characteristically in an oblique arrangement. Perforation plates are exclusively simple. Vessel pitting is vestured and tyloses are abundant. Transversely, the tissue consists of uniseriate homocellular rays, consisting exclusively of procumbent parenchyma cells. Pits between vessels and ray cells are large and rounded. Axial parenchyma is predominantly paratracheal, vasicentric and diffuse.

South African grown *Eucalyptus grandis* has a rather low density compared to other locally grown Eucalypts (0,69g.cm^{-3} air-dry) but is relatively strong, elastic and tough, but not very hard.

The density of the wood varies considerably both within trees and also from tree to tree. At breast height, density decreases initially with age followed by a pronounced increase towards the bark (Taylor, 1973). However, the effect of distance from the pith (age) on density seems to change with increasing height above ground level. In fourteen-year-old trees, Taylor (*ibid.*) observed only a small effect of age at a height of 10,7m while at

23m height there was an almost linear decrease in density as distance from the pith increased. Rate of growth does not appear to have any effect on wood density within trees. As regards the effect of height in tree on wood density, Taylor (*ibid.*) observed a sharp decrease from 1,5m to 4,6m above ground level, followed by a pronounced increase with increasing height.

Wood density varies considerably from tree to tree. Trees with high wood density usually exhibit a higher density at every sampling point than trees with a low wood density. Since the between-tree variation in wood density is often not accounted for by any environmental factor, a large part of the variation must be attributable to genetic factors (Taylor, 1973).

Taylor (1973) found that both fibre length and fibre diameter increase with distance from the pith. Fibre length is not much affected by height above ground, but the diameter of fibres is significantly less at 22,9m than at 10,7m.

Variations in strength in this wood are largely the result of the considerable variations in wood density (Scott, 1940, 1950 as reported by Poynton, 1979). The inner core, approximately 75 to 150mm in diameter is usually low in strength because of its low density, brashness and knottiness. Towards the circumference the strength increases commensurate with its density. However, studies by Priest *et al.* (1981) on 12-and 24-year-old material from the Letaba district indicated no significant difference in modulus of elasticity between the two age groups although the density of the 12-year-old material was appreciably lower when compared to that of 24-year-old trees. This could possibly be due to the higher content of extraneous components in the older material, which increases the density of the wood but contributing nothing towards the mechanical strength.

Mature green timber has a moisture content of about 97 per cent, while the moisture content of 12- to 15-year-old timber is about 88 per cent (van Vuuren *et al.*, 1978). The timber seasons well. Little degrade develops during seasoning apart from an

increase in the length of existing splits and the amount of spring. However, wood of older trees may tend to warp and corrugate rather badly during seasoning. For economic reasons kiln-seasoning of boards from the green state is not recommended, especially in thicknesses of more than 25mm. The best results are obtained when thicker material is first air-seasoned followed by kiln-seasoning. Boards of 25mm thick can be air-seasoned to equilibrium moisture content, but if the material is to be used for joinery, panelling or furniture, the boards should first be air-dried under cover for two to three months followed by a conditioning period in a kiln to reduce the moisture gradient and drying stresses in the boards (van der Westhuizen, 1978). The radial, tangential and longitudinal shrinkage from green to a 10 per cent equilibrium moisture content average about 4,24; 9,40 and 0,23 per cent respectively.

The working properties of the wood vary with density. In general, the wood works easily, although it is inclined to be tough. It saws freely and cleanly, planes to a smooth surface, scrapes and sandpapers well, bores, mortices and glues easily and takes stain and polish readily. It nails well, especially when nails are driven in at high speeds.

Both the sapwood and the heartwood are not naturally durable and timber should be treated with a suitable preservative if the timber is to be used for exposed work. It is also good practice to treat green timber with an insecticide before stacking it for air-drying in order to prevent attack from Lyctus beetles and fungi.

As a result of the good stem form of *Eucalyptus grandis* the logs are usually straight, free from excessive taper and knots. The bark strips very easily provided stripping is done soon after felling. This species is very prone to high levels of growth stress and, as a result, severe end-splitting commonly develops in logs as a result of stress relief during felling and log preparation. During sawing the boards tend to distort and split

down the middle, This is particularly pronounced in boards originating from the central parts of the stem. Generally the split length in board ends decreases with an increase in distance from the pith (Priest *et al.*, 1981).

2.5 Uses

Eucalyptus grandis was introduced into South Africa mainly as a source of mine props and timbers. Today it is considered as a most versatile utility timber being used for light construction work, framing, shelving, panelling, ceiling, flooring, joinery, furniture, toys, crates, boxes, pellets, poles scaffolding, fence posts and droppers (van der Westhuizen, 1978). Utility furniture made from it has a pleasing appearance, gives excellent service and is in demand for office, childrens' playroom, kitchen and other uses (Poynton, 1979). It is also pulped on a big scale for the manufacture of hardboard, paper and rayon. The mines consume large quantities of wood for pit props, mat packs and lagging. In Angola it is used as a fuel to fire steam locomotives and in Zimbabwe it is used to cure tobacco (Poynton, 1979).

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CHAPTER THREE

NATURAL DEFECTS COMMON TO *EUCALYPTUS GRANDIS*

3.1 Knots

Although plantation grown *Eucalyptus grandis* usually exhibits good self-pruning properties, branch-shedding in the lower portions of the stem only starts taking place two to three years after dying. These branches give rise to sound knots for 50 to 70mm of their length from the pith, often with a deep check along the line of their own pith. Their distal ends are usually dead and decayed, often with a plug of corky tissue mixed with kino at their ends. These knots occur mainly in the juvenile wood and where trees are grown on a short rotation basis, for instance for the production of mining timber, pulpwood and smaller poles, their presence is not considered of great importance.

When trees are grown on a longer rotation, for instance for the production of transmission poles, they will contain these small knots inside the lower portions of the stems as well as larger exposed ones higher up in the stems. These latter knots could harbour fungi deep inside the stem which may become active when the pole is in service and destroy the pole from the inside. This could be overcome by keeping the pole long enough in the hot preservative for the heat to penetrate to the centre of the pole to kill the fungi and their spores.

In mature trees, mostly used for the production of saw timber, the branches are usually large and scattered in the crowns giving rise to large, tight knots. In sawn timber these knots usually develop deep checks during seasoning.

Lower down in the tree stem, the presence of dead, decayed knots causes serious degrade in boards cut from near the centre of the stem. Cross-fractures are often present in association with the loose knots (De Villiers, 1973).

3.2 Brittle Heart

Brittle heart is often found in the central parts of stems of trees of this species older than 35 years. In young stems its occurrence is usually negligible.

Brittle heart is characterised by the abnormal brashness of the wood resulting from the presence of numerous microscopic compression failures in the cell walls. When present, brittle heart is irregularly distributed in the centre of the cross-section of the stem. Its intensity diminishes with distance from the pith.

This defect is apparently the result of high levels of longitudinal growth stress in the peripheral layers of the stem. If these stresses are sufficiently high, the counterbalancing compressive forces in the central part of the stem may exceed the maximum crushing strength of the wood, causing numerous slip planes and compression failures (Malan and Toon, 1980; Hillis, 1978; Hardie, 1974; de Villiers, 1973; Dinwoodie, 1966).

In South Africa this defect is not considered of much importance as our trees are usually felled before the extensive development of this defect.

3.3 Kino rings

Almost all Eualypts produce kino and it is mostly enclosed in ducts or veins, and pockets. It exhibits the general characteristic of being a viscous yet mobile orange-coloured exudation which, on exposure to air, becomes a hard, dark-coloured, amorphous, glasslike substance (Malan and Toon, 1980).

Damage caused to the vascular cambium by fire, insects, branch fall, falling trees and extraction equipment, etc., results in the development of numerous tangentially arranged rows of traumatic kino veins which follow the growth ring. These rows of veins are commonly referred to as kino rings.

In *Eucalyptus grandis* they are infrequently present and in general do not constitute a defect of much significance. When they do occur in considerable numbers, they have an adverse effect on timber strength and pulp yield, result in the bigger consumption of pulping chemicals and interfere with the bleaching process.

3.4 Variations in wood density

The density of *Eucalyptus grandis* varies considerably both within and between trees. In South African trees density decreases sharply with height from about 1,5m to about 5m, followed by a consistent increase higher up in the tree. Both the rate of increase beyond 5 m height as well as mean tree density vary from tree to tree. A large part of the observed variation between trees does not seem to be related to environmental factors and must, therefore, be attributed to genetic factors.

Density increases considerably from the pith outwards as a result of changes in the vascular cambium with age; a phenomenon found in many timber producing species. The rate of density increase from pith to bark decreases with height. At high height levels an almost linear decrease in density can be expected (Taylor, 1973).

Density is considered by both the mechanical and the chemical wood processor as one of the most important wood properties determining wood quality. Density is strongly related to the ratio of fibre diameter and cell wall thickness, number and size of vessels and many other characteristics important to the pulp and paper manufacturer.

The timber manufacturer and user are concerned with shrinkage and strength, among other things, and both these features are strongly related to density.

Variations in density in *Eucalyptus grandis*, as described, implies large variations in wood quality between as well as within trees causing serious utilization problems. For instance, the manufacturer of laminated beams and structures has to sort timber into density classes in order to eliminate severe drying stresses in the glue lines. As a result of the density variations in trees, the strength properties of *Eucalyptus grandis* also vary considerably, often necessitating strict selection of sawn pieces to meet end-user wood quality requirements.

3.5 Spiral and distorted grain

Interlocked grain, consisting of zones of wood with alternating spiral grain, has been observed in radially sawn *Eucalyptus grandis* boards, giving it an attractive striped figure. However, if the grain angle in the alternating spiral grained zones departs more than 4-5° from the vertical axis of the board, it is virtually impossible to obtain a smooth surface except by sanding (De Villiers, 1973).

Wavy grain also occurs in *Eucalyptus grandis*, giving it an attractive appearance. Excessively wild and distorted grain seldom occurs in trees younger than 25 to 30 years and is therefore not a serious problem under present South African conditions.

3.6 Growth stresses

End-spliting in logs, poles and sawn timber as a result of high levels of growth stresses, can be considered as one of the major defects in Eucalypts and more particularly in *Eucalyptus grandis*, outclassing all other natural defects in terms of its effect on sawn yield as well as on board length and width.

Growth stresses are generated as a result of the lignification of the S2-layer of fibre walls after the formation of the framework of the microfibrills (Boyd, 1950 Part III). This causes a transverse swelling of the cell wall and an associated longitudinal shrinkage. Since the mature secondary xylem restricts the decrease in length, each successive layer added to the stem is laid down in a state of tension. This eventually causes a longitudinal stress gradient across the radius varying from a longitudinal tensile stress in the outer layers of the stem with increasing intensity towards the periphery, and a longitudinal compressive stress in the central parts of the stem of increasing intensity towards the pith (Figure 4.1).

In the standing tree stresses are in complete balance. On cross-cutting the stability is upset causing the tensile zone in the stem to shorten and the central zone to expand. This causes the development of splits at the ends of logs (Figure 4.2).

End-splitting in logs usually starts developing immediately after cross-cutting, reaching close to maximum values within three days thereafter. In severe cases splits can develop through the entire length of the log, causing the log to divide into separate sectors.

The length of existing splits in logs tends to increase during sawing as a result of further stress relief. Studies by Priest *et al*. (1982) and other research workers revealed that the length of splits in boards decreases rapidly with an increase in distance from the pith. Splits in radially sawn boards often open so widely that boards split almost in two longitudinal halves with each half sprung in an opposite direction (De Villiers, 1973) (Figure 3.1).

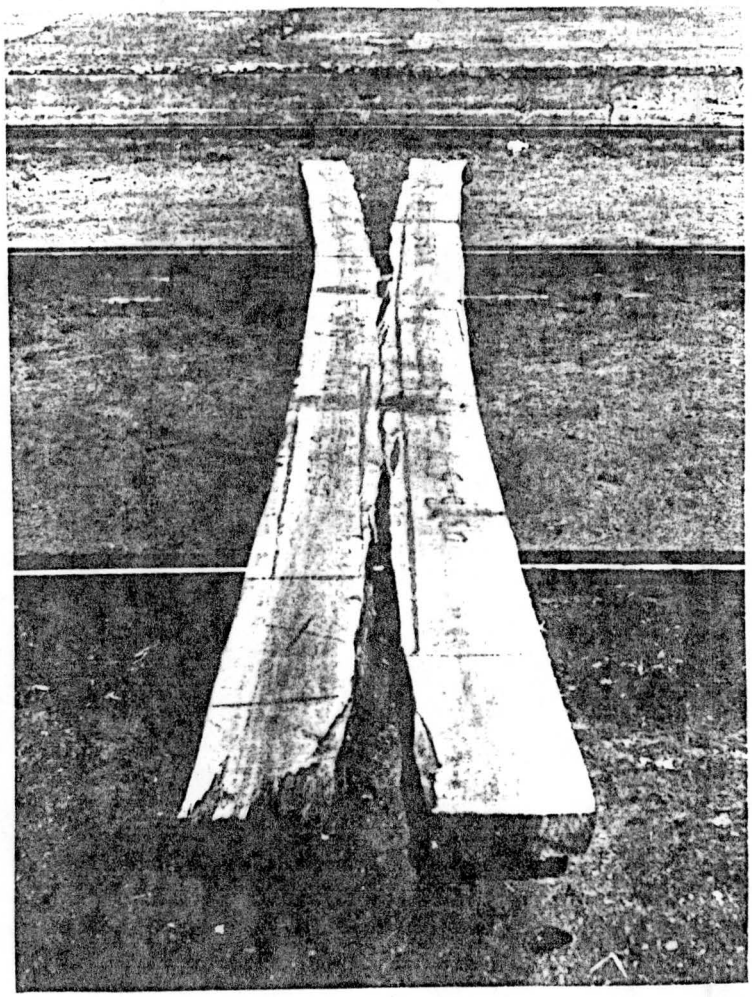

Figure 3.1:- Splitting in a true radially sawn *Eucalyptus grandis* board.

End-splitting in transmission and telephone poles is responsible for considerable losses in the plantations and at impregnation plants as it is often necessary to remove excessively split ends before treatment.

As far as mining timber is concerned, and especially where the timber is used in the round as props, badly split ends provide poor bearing surfaces. Timber for mat packs is usually slabbed on two sides and cross-cut into short lengths when green and allowed to dry in the finished lengths. The number of pieces rejected as a result of splitting can be as high as 40 per cent (De Villiers, 1973).

Various attempts to reduce the levels of growth stresses in trees in order to reduce the amount of splitting in logs, have met with limited success. The circumferential grooving technique has proved one of the most promising methods to reduce log end-splitting (Barnacle and Gottstein, 1968; Conradie, 1980). However, the awkwardness of applying the grooves, the additional harvesting costs involved, and the practical problems encountered at the wood processing plants as a result of the presence of grooved ends in logs, have discouraged the implementation of this technique as a general practice.

In Chapter four present knowledge on growth stresses and related aspects is reviewed in detail.

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CHAPTER FOUR

GROWTH STRESSES - A REVIEW OF LITERATURE

4.1 Introduction

Growth stresses develop in the normal wood of both softwoods and hardwoods but they are particularly severe in a limited number of hardwoods, i.e. *Eucalyptus spp.*, *Shorea spp.*, *Fagus spp.*, *Carya spp.*, *Populus spp.* and a few tropical genera (Nicholson, 1973b).

The release of high levels of growth stresses in these trees cause failures or splits and deformations in logs and sawn boards, resulting in severe degradation in timber quality, and yield losses.

Various aspects of growth stresses, i.e. their nature, origin, distribution, control and effect on yield and quality, have been studied intensively since the beginning of this century. In 1966 Dinwoodie reviewed the then existing information obtained from many experiments and observations. In this review an attempt will be made to summarize existing knowledge on growth stresses. Since the mechanical action of growth stresses in normal wood is closely related to the action of tension wood (Wilson and Archer, 1977), the latter will be reviewed as well when related aspects are considered.

4.2 The nature and cause of growth stresses

Growth stresses develop within woody tissue as a result of the tendency of the differentiating cells to contract during cell maturation. Because the differentiating cells are in firm contact with the adjacent, mature xylem, tensile stresses are generated in each newly formed layer of cells. As this action takes place in each successive layer added to the xylem, the rest of the xylem is progressively compressed. This causes a

pith-to-bark stress gradient which varies from a compressive stress in the central part of the stem, which decreases to zero at a point one-half to two-thirds of the radius from the pith, and a tensile stress increasing from the neutral point towards the cambium (Figure 4.1). Since each row of new cells is laid down under tension, it is a cumulative effect, with the result that the central part of the stem may eventually be compressed beyond the elastic limit of the wood. This causes the development of numerous compression failures in the cell walls, resulting in a defect commonly known as brittle heart.

The nature and origin of growth stresses in normal, erect stems have received considerable attention since investigations in this field started. At present there is little disagreement over this aspect.

Martley (1928), tested his own hypothesis that stresses could be the result of the mass of the tree and concluded that stresses caused by the mass of the tree could only account for a fraction of the observed magnitude of growth stresses.

Münch (1938), working mainly on compression wood, seems to have been the first to come to the conclusion that stresses in reaction wood are generated by the longitudinal shrinkage of the cell walls of wood cells with a concurrent swelling of their transverse wall. This happens as a result of the deposition of solid substances in the lateral intermicellar spaces of the cell wall during lignification.

Münch's hypothesis was later used by several research workers like Jaccard (1938), Mayer-Wegelin and Mammen (1954), Lenz and Strässler (1959) to explain the growth stresses in normal erect stems.

Jacobs (1938, 1939) explained initially that growth stresses are generated as a result of fibre shrinkage as the fibres solidify from the gelatinous cambium, but later (1945) proposed that growth stresses arise as a reaction to the tension in the sap stream.

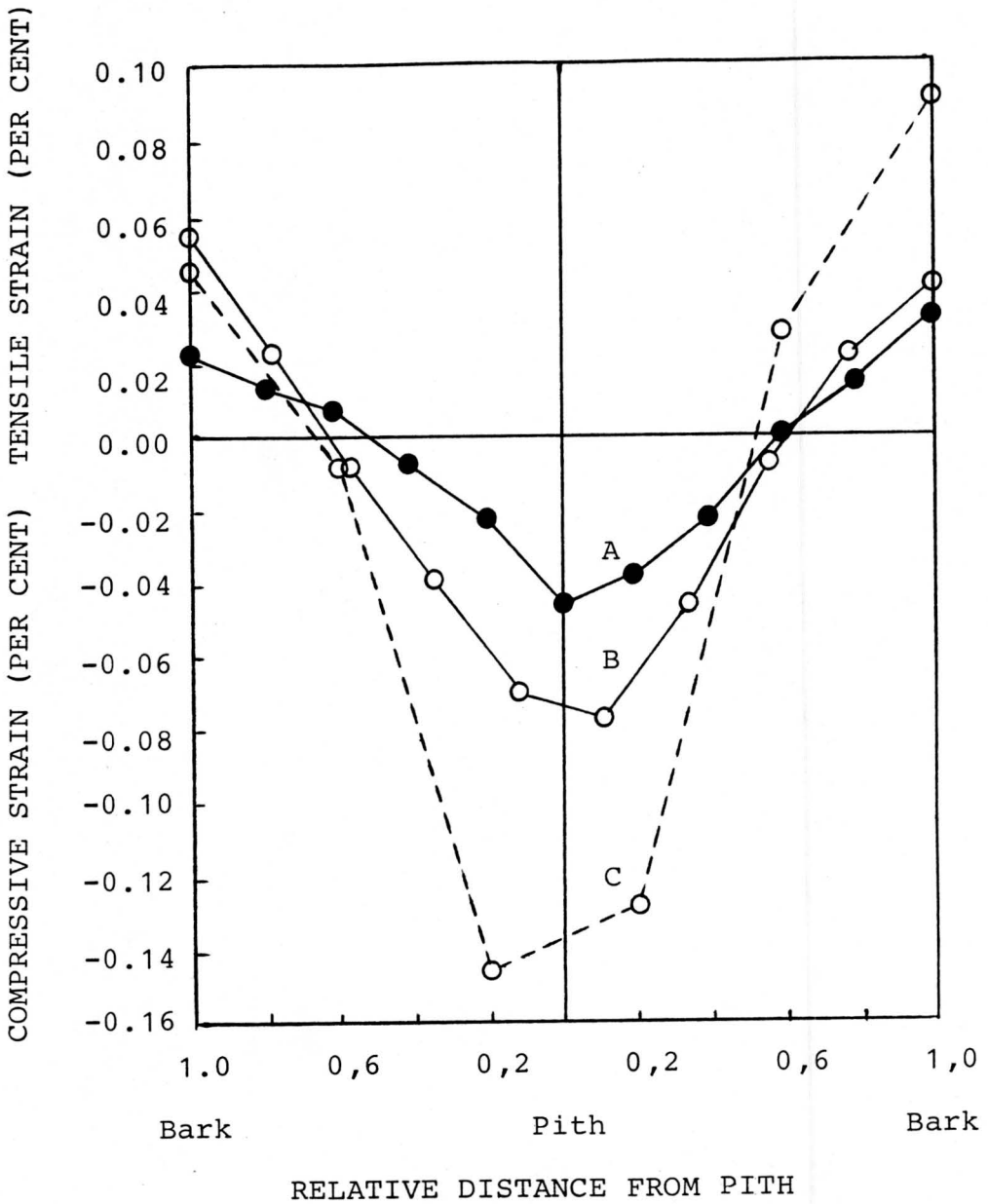

Figure 4.1:- Distribution of growth strains in normal wood of *Chamaecyparis obtusa* (A), *Cryptomeria japonica* (B), and *Quercus glauca* (C) (Watanabe, 1965).

Early studies by Koehler (1933) suggested that growth stresses could be generated by factors such as greater circumferencial than radial growth, reduction in the turgidity of older tissue, and chemical changes.

Boyd (1950, Part III) critized these theories mainly on the basis that differential stresses should be absorbed by the cells before the secondary wall is formed, and that the turgidity of the cell does not decrease as the diameter decreases. He also critized Jacobs' (1945) proposal on grounds that as suction forces are greatest at the top of the tree and lowest at the bottom of the tree stem, stresses should show a similar distribution. This is not the case. Jacobs (1945) also proposed that vacuolation forces could be the cause of growth stresses, but this has also been rejected by Boyd (1950, Part III) as these forces are not sufficient to produce the magnitude of stresses already observed.

Perkitny *et al.* (1951) suggested that moisture variations in the peripheral cells could account for the generation of growth stresses but this has also been rejected.

Kübler (1959, Part 1) agreed that the shortening of the newly formed cells is the cause of growth stresses but maintained that stresses are formed prior to lignification. He could, however, not give another physiological explanation for the shortening of the fibre.

Watanabe (1965) presented a hypothesis to explain cell shortening in the outer layers of the tree which agreed broadly to that proposed by Münch (1938), namely that the swelling of the cell wall is caused primarily by lignification. He also suggested that the degree of extension or contraction was determined by the microfibril angle.

Grozdits and Ifju (1969) related the progressively increasing density and tensile strength in differentiating coniferous xylem to the stages of development of the cellulose framework of the cell wall and to the extent of its lignification. Boyd (1972,

Part V) used their data together with other relatively new data on anistropic shrinkage to test Münch's and Watanabe's hypotheses which were the most favoured at that stage. His calculations of their data have shown that on the average differentiating cells expand about 22 per cent from the completed primary wall to the end of the lignification process of the primary and secondary walls. Wardrop (1971) pointed out that lignification even continues for some time after the cellulose framework is formed. Chemical estimates by Grozdites and Ifju (1969) of the lignin content of samples taken from various stages of the cell wall differentiation confirmed this.

Studies by Frey-Wyssling (1954, 1955) and others (as reported by Boyd, 1972, Part V) have shown that the cellulose microfibrils are initially closely aggregated in the cell wall and form a series of lamellae which generally are continuously around the cell wall and in close contact with the capillary systems within and between the microfibrils. Any substance deposited in these open spaces will eventually fill them up and start to force the microfibrils apart. This would cause the cell wall to swell in thickness and at the same time increase the overall cross-section of the cell.

Any changes in the dimensions cells would be resisted by the mature tissue to which it is firmly bonded. This would impose a restraint on the differentiating cells and at the same time a strain in the mature wood. Boyd (1972, Part V) estimated the potential longitudinal stress as a result of lignification and found that it is of the same nature and magnitude as the values already measured for longitudinal growth stress. He also indicated that this not only applies for all other types of growth stresses (tangential and radial), but that it also applies for both hardwoods and softwoods.

The fact that each successive layer is laid down in a state of tension explains the internal stress profile that is normally observed in erect stems. The outside layers are under tension, while the central part of the stem is under compression. Within

each of these stress zones a stress gradient exists increasing from the transition point inwards and outwards. The longitudinal tensile force continuously being generated within successive layers of newly formed cells as the tree grows, results in a continuous increase in the existing compressive stress of the core. At the same time the cross-sectional area of the compression zone will increase. As the tree grows, the central parts of the stem will be compressed beyond its elastic limit causing the formation of brittle wood. Also in this case the cross-sectional area of the brittle zone will increase as long as the tree grows and its diameter increases.

The mean level of longitudinal growth stress varies within as well as between trees. (The latter will be discussed in the next section.) The mean level of stress in a tree does not seem to be determined by stem straightness. Peripheral stress patterns and pith-to-bark stress profiles appear to be closely related to the requirements of the tree for mechanical support (Nicholson, 1973b; Watanabe, 1965). Both authors demonstrated that in leaning trees, or trees with unbalanced crowns, the stress pattern becomes asymmetrical. Nicholson (1971b) has found within-tree surface growth strains varying from approximately 1 to 82 on the surface opposite to the direction of lean. Hillis (1978) reported stress variations ranging from 3,9 to 5,5mPa and 1,9mPa and 44,7mPa in two non-leaning, 31-year-old *Eucalyptus regnans* trees. A similar variation has been observed for a 70 year old *Eucalyptus obliqua* tree. Studies by Nicholson (1973b) on 41 *Eucalyptus regnans* and 12 *Eucalyptus obliqua* trees showed differences of up to three times between trees.

Variations in longitudinal growth stress with height in the tree have, until recently, been studied to a limited extent. Jacobs (as reported by Boyd, 1950 Part III) observed no variation in growth stress with height. Nicholson (1971b) and Yao (1979) reported only a weak relationship between level of growth stress and height in the tree. Malan (1979a), using log end-splitting as parameter for growth stress, reported a rapid increase in splitting from ground level to about 8m height followed by a

gradual decrease towards the top of the tree. This pattern, however, varied from tree to tree while the general pattern also varied between the three geographical regions studied. Chafe (1981) found both longitudinal growth stress and growth strain to increase with height above ground level but this could not be proved statistically. He, nevertheless, speculated that this could be the reason why upper logs of *Eucalyptus regnans* tend to split more.

4.3 Factors affecting mean level of growth stress in individual trees.

4.3.1 Introduction

Large differences in mean levels of longitudinal growth stress are known to exist among trees, even among those growing within the same general environment (Nicholson, 1973b).

Log end-splitting in South African grown *Eucalyptus grandis* is characterized by an enormous between-tree variation (Figure 4.2). Apart from a very large variation between trees growing under apparently uniform conditions, large variations have also been experienced between groups of trees growing under similar climatic conditions but on different site qualities (Malan, 1979a). Differences have also been found between geographical areas, *viz* the North-Eastern Transvaal, Eastern Transvaal and Zululand (Malan, 1979a).

4.3.2 Silvicultural practices

Very little is known about the effect of silvicultural treatments on growth stress levels. Marsh and Burgers (1967) recommended conservative thinnings in the first half of the rotation of thirty years, followed by thinnings of sufficiently increasing intensity in order to maintain an even growth rate. Hillis (1978) pointed out that plantation grown trees should have lower mean stress levels and within-tree variation in comparison with

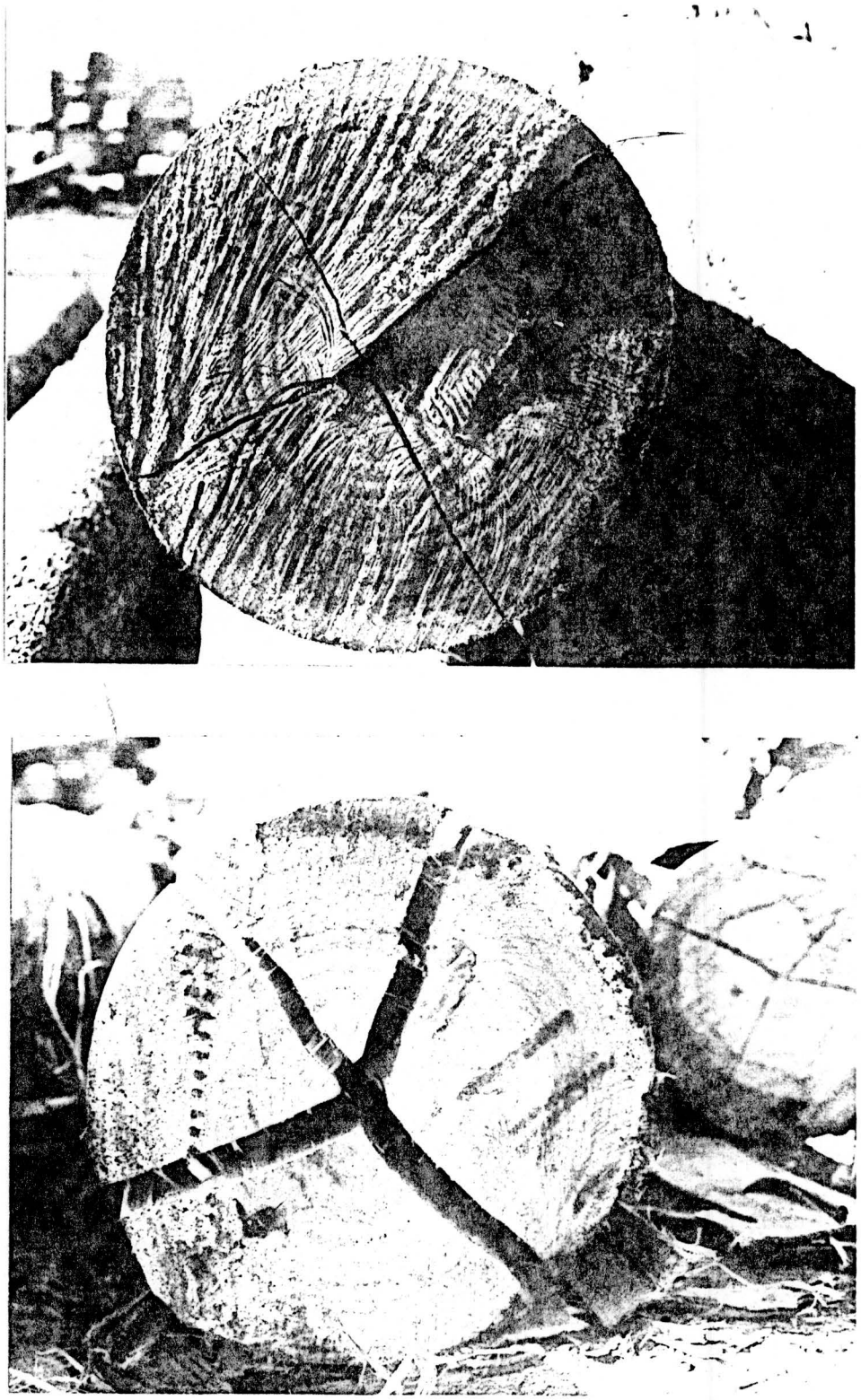

Figure 4.2:- Difference in the amount of end-splitting in the faces of logs cut from trees from the same environment.

trees growing under natural conditions. Material collected from a 12 year old *Eucalyptus grandis* pruning trial showed "a sharp increase in degrade due to spring, which appeared to be directly proportional to pruning intensity" (Lückhoff, 1967).

Investigations carried out on the same material at rotation age showed no significant relationship between pruning intensity and the degree of end-splitting in logs (Bredenkamp *et al.*, (1980). Studies by Malan (1979a) revealed a strong negative relationship between crown proportion and splitting in *Eucalyptus grandis* trees of varying ages. Priest *et al.* (1981) later experienced the same phenomenon in mature *Eucalyptus grandis* trees.

Results on the effect of growth rate on splitting are very conflicting. Most researchers are convinced that fast growing Eucalypt trees in general tend to exhibit more splitting than slow growing Eucalypt trees (Hardie, 1974; Hillis, 1973; Hillis, 1978; Edwards, 1973). On the other hand, Ferrand (1982) observed reduced growth strain in Australian grown *Eucalyptus delegatensis* and *Eucalyptus nitens* grown at wide spacings and in trees grown on high quality soils. Moderate thinning did not effect growth strain, but a heavy early thinning decreased it.

Although no formal studies have been carried out to investigate the effect of site quality on splitting, there is general agreement among South African foresters that the degree of splitting varies from site to site depending on the quality of the soil. Trees growing on poor sites usually exhibit less splitting than trees growing on good quality sites. A variation in the degree of splitting is also observed in trees growing on sloping sites where there is usually a marked variation in soil quality.

Studies on growth stress differences in *Eucalyptus regnans* and *Eucalyptus obliqua* have indicated that the mean level of longitudinal growth stress on the tree periphery appeared to vary independently of both rate of growth and environmental factors such as exposure to wind, stand density, site and elevation (Nicholson, 1973b).

Bielczyk (1953), studying end-split variations in Polish grown Beech, observed distinct differences in split area between trees originating from two different geographical areas. No relationship was found between split size and factors like green moisture content, heartwood content, log length and log diameter.

4.3.3 Season

A strong relationship has been found between growth stress levels and soil moisture. Investigations carried out in Australia on *Cryptocarya erythroxylon* and in South Africa on *Eucalyptus grandis*, have shown that growth stress levels are intensified during periods of high rainfall when soil moisture is freely available (L.O. Reinstorf; W.E. Hillis and P.J. Fitzgibbon as reported by Hillis, 1978). Differing results have been obtained by Malan (1979a) showing log end-splitting in *Eucalyptus grandis* growing in the North-Eastern Transvaal to be the most severe in the hot, dry months of early summer. These results suggested that higher than normal levels of growth stresses are generated in a period of increasing cambial activity when trees are growing under conditions of severe soil moisture shortage. The magnitude of log end-splitting dropped rapidly from October to December with the start of the summer rain and remained at a constant level for the rest of the summer season. This finding has been re-examined in this study (Chapter six).

Okuyama *et al.* (1981) observed a seasonal variation in both peripheral longitudinal and tangential growth strains. Surface strain measurements were carried out on 25-year-old Sugi (*Cryptomeria japonica* D. Don.) in the Shitara district of Japan in early June when the rate of growth is at its maximum, late August when there is a decrease in growth rate and when late-wood is produced, November when the cambium has virtually ceased functioning and early March just before the spring growth flush. Longitudinal surface strain was found to be signicantly lower in June when cambial activity reached a maximum. In August the

strain values were much higher and this remained virtually at the same level for the rest of the year. Tangential surface strain increased gradually until the dormant season in March.

Longitudinal and tangential strain measurements carried out on the growth layer of the previous year remained fairly constant throughout the year with mean values of the same magnitude as the maximum values recorded for the current year. The level of growth stresses was found not to be related to the rate of annual growth.

It has long been said that plants grow with equal efficiency provided the soil moisture is held within the range varying between the point of field capacity and the permanent wilting point. Yet it is known that water stress in the plant is influenced by the water stress in the soil and this influences a number of physiological processes like transpiration, stomatal aperture, photosynthesis, respiration, chemical composition of the tissue, nitrogen metabolism, etc. The one of concern is the effect of water stress on the plant growth. There are many examples showing that water stress can affect the growth of plants at levels well above the permanent wilting point.

Studies by McMichael *et al.* (1972) and El-Beltagy *et al.* (1974) have shown that a strong positive relationship exists between the level of the plant hormone ethylene and water stress in plant tissues. Leopold *et al.* (1972. As reported by Nelson and Hillis, 1978) reported that the imposition of bending stress on branches of *Pinus strobus*, *Pyrus malus* and *Prunus persica* increased ethylene levels within the stressed branches. This suggests that ethylene may act in trees as a natural hormonal stimulator of radial growth associated with physical stress and may be involved in the formation of reaction wood. Nelson and Hillis (1978) and Nelson *et al.* (1978) found a strong relationship between the level of ethylene and the presence of thick-walled and tension wood fibres in Eucalypt and Poplar.

The precise role of ethylene and auxin (which is generally considered to stimulate tension wood formation if present in deficient quantity) is not fully known. It was found in only a few of the higher plants that ethylene is produced independent of auxin supply. The study by Nelson *et al.* (1978) raised the possibilty that the induction and maintenance of tension wood formation may be a response to either a high ethylene level or to a high ethylene-low auxin concentration.

A strong relationship has been found between peripheral stress and the proportion of thick-walled fibres (Nicholson *et al.*, 1975). With this in mind it seems quite possible that growth stress levels are directly or indirectly controlled by the level of ethylene in the plant. In the case of leaning trees the production of ethylene is stimulated on the wind side of the tree, causing the formation of tension wood and abnormally high stress levels in order to support the tree.

4.3.4 Genetics

The extreme differences occurring between trees growing within the same general environment (Nicholson, 1973b; Malan, 1979a) suggests that growth stresses may to some extent be under genetic control.

In the South African tree-breeding programme lack of end-splitting in logs was always an important criterion before trees were accepted for breeding purposes. Although little was known about the genetic influence on end-splitting in logs in the early days, it was hoped that genetic manipulation would be possible (Nel, 1962; Hodgson, 1967; van Wyk and Roeder, 1978).

Breeding with *Eucalyptus grandis* started off slowly in 1962 because of the new grafting and pollination techniques which had to be developed, and the slow process of screening phenotypes on sawn timber recovery (van Wyk, 1977 and 1980; Banks and van Vuuren, 1976). This, of course, delayed the establishment of progeny tests.

Early *Eucalyptus grandis* progeny trials consisted of small numbers of families and were often inadequately replicated. In spite of the shortcomings of these trials, attempts were made to study family variation and to obtain an estimate for end-splitting heritability (Malan, 1979a).

Significant differences in log end-splitting have been found among a series of 9 open-pollinated families. Calculations indicated that the heritability might be between 0,15 and 0,20. Furthermore sawn boards produced from logs originating from one of these trials exhibited significantly less splitting compared to that in boards cut from logs originating from normal commercial stands (unpublished records, South African Forestry Research Institute).

Other workers have also considered the variations in growth stress to be due mainly to genetic factors. Rudman *et al.* (1969) and Higgs (1969) have found wood density in Eucalypts to be under significant genetic control. Since good correlations were found between wood density and level of growth stress (Nicholson *et al.*, 1972) it was concluded that growth stress intensity must to some extent be genetically controlled (Nicholson, 1973b) This conclusion was in fact confirmed by studies on a number of open-pollinated families of *Eucalypts regnans* (Waugh, as reported by Hillis, 1978).

Work on growth stresses in Poplar indicated a highly significant clone-locality interaction which means that clones react differently to changes in locality (Wangh, 1972). It was concluded that choice of site as well as genotype and species may have an important bearing in establishing future forests if we wish to reduce growth stress problems.

Little correlation was found between level of growth stress and environment, genetic and tree factors in Beech (Lenz and Strässler, 1959).

4.3.5 Environment

Several workers have considered the importance of growth stress in reorientating the stem in order to alter the crown to the most optimum position in relation to its immediate environment (Sinnot, 1952; Robards, 1969; Nicholson, 1973b). Nicholson (*ibid.*) suggested that a tree may not alter its vertical orientation without first changing the stress within its stem. As only the differentiating cells can respond to an external stimulus, the longitudinal stress within these cells seems to be the most effective mechanism to control stem movement in order to orientate the crown to an optimum position.

It is known that climatic and environmental factors exert a direct influence on crown development of the tree, and via the crown they will have an indirect effect on wood formation (Larson, 1963). Since the crown is the main receptor of environmental and climatic effects, it seems a logic starting place to interpret their effect on wood properties and stress levels.

It is known that the environment is constantly changing over the long-term as well as over the short-term. This includes seasonal changes as well as long-term climatic changes. Wood properties can also be affected by site factors, or changes in the stand structure brought about by silvicultural or natural means. It is clear, therefore, that trees, even in an even-spaced stand growing under apparantly uniform conditions, are exposed to varying environmental conditions fairly soon after planting. Throughout the life of a tree, environmental changes are constantly taking place and the response of the tree to the environment is likewise changing. As the crown is the main receptor of environmental influences, any environmental effect on the crown will trigger off a series of physiological processes which eventually will alter wood formation in the stem in an attempt to move the crown or to maintain its existing position.

It is generally agreed that growth stresses serve the purpose of stabilising the tree (Nicholson *et al.*, 1973b). It therefore seems reasonable to expect that any crown factor adding to the masss of the crown or increasing wind induced drag forces, will increase the stress levels in the tree stem. However, if a relationship could be found with certain crown properties, it would be difficult to establish which of the many environmental factors acting on a tree is predominating. Nevertheless, these environmental factors interact in various ways to ultimately produce particular patterns of crown growth that may be related to the degree of splitting in the log ends of a tree. Crown size, mass and symmetry and particularly the extent to which it is exposed to external forces, might to some extent determine the stress in a tree.

Existing evidence suggests that the level of growth stress in individual trees is controlled by both environmental and genetic factors. There is still an urgent need to gain a deeper understanding of the factors controlling stress levels in trees, so that the most efficient technique(s) of stress reduction can be devised.

4.4 Methods of growth stress assessment

Methods for determining longitudinal growth stress within tree stems are to measure the dimensional change (strain) resulting from stress relief. By determining the modulus of elasticity of the wood under compression parallel to the grain, using material end-matching the position of strain measurement, the stress equivalent of the strain measured at a particular point in the stem can be computed.

Jacobs (1938, 1939, 1945) was the first to study the magnitude and variation of longitudinal growth stress in tree stems. He demonstrated the presence of growth stress by preparing diametrical planks (planks that include the pith) across the stem, subdividing them into strips running parallel to the longitudinal axis of the stem, and measuring the length changes in the strips resulting from the stress relief (see: Jacobs, 1965

Figure 1). Watanabe (1965) and Giordano *et al.* (1969) applied the same method of determining the longitudinal growth stress distribution across the radius of the stem in their studies.

Although this method has provided useful information about the longitudinal growth strain and stress distribution in trees, several workers have warned against the complications that arise as a result of the redistribution of strains that takes place in the diametrical plank when cut from a log (Gillis, 1973; Beck, 1974; Vendhan and Archer, 1977; as reported by Post *et al.*, 1980). Their analyses have shown "that removing a diametrical plank from a log is statistically equivalent to applying a net force and/or moment to each end of the plank in order to cancel the in-tree forces". This means that a uniform extension of the in-tree plank would take place resulting in higher residual tensile strain and stress values in the newest wood and lower compression strain and stress values near the pith that really exists in the tree. Also end effects on diametrical planks can be serious, provided certain precautions are taken to minimize these effects (Post *et al.*, 1980).

An extension of Jacobs' method was subsequently proposed that would yield longitudinal growth strain readings at many points over a substantial part of the stem cross-section. In this method the log is cut into boards and the boards into strips. Length changes are measured in both the board stage and strip stage, giving information as regards log-to-board, board-to-strip and log-to-strip growth strains. Modulus of elasticity was determined by testing samples cut from the strips in compression parallel to the grain, and used to estimate the level of stress that existed in each strip. A similar principle was used by Chardin and Sales (1983) to study cross-sectional stress distributions in three tropical species grown in French Guyana.

Nicholson (1971a) proposed a technique for the rapid measurement of growth strain on the periphery of stems and logs. In this technique a mechanical strain gauge was used to assess strains. Stress relief to allow surface strain measurements was obtained

by removing a rectangular segment approximately 19mm deep, 19mm wide and 89mm long. A specially made jig was used to return the segment to its original "in-log" curvature before the final strain reading was taken (see: Nicholson, 1971a Figure 1 to 6).

Because of the rapid assessments that can be done by means of this technique, patterns of stress and strain can be obtained about the circumference and along the length of logs. Comparisons can be made between many standing trees thus enabling the identification of low-stressed trees for selection for genetic improvement and various other studies. Since this technique is a non-destructive means of assessment, it also allows the reassessment of stress when changes in stress in the same log or stem are to be investigated. Saurat and Guéneau (1976) used a less rapid but slightly more accurate extensiometric technique to measure peripheral growth strains in Beech. The same extensiometric transducers and methods were used to evaluate the modulus of elasticity in the field in order to transform strain into stress.

Boyd (1950, Part I) measured growth strain at various radial positions within parallel-sided slots cut from the bark to the pith (see: Boyd *ibid*. Figure 1). Stress relief was achieved by cross-cutting the log successively closer to the slot. When the cross-cut was very close to the slot, the total strain recorded at the various radial positions gave approximate values of total longitudinal strain, thus providing information as regards the radial distribution of longitudinal growth stresses. Kübler (1959, Part 2) and Wilhelmy and Kübler (1973a and b) performed similar experiments by drilling a hole radially into the stem and measuring the diameter changes at various radial positions by means of a special probe fitted with electric strain gauges, as cross-cutting towards the hole progressed (see: Kübler, 1959 Part 2 Figure 4).

Polge and Thiercelin (1979) performed experiments to study changes in the diameter of increment cores as a result of growth stress relief, in relation to the level of stress. A highly significant straight line negative relationship was found between actual longitudinal growth strain and tangential core diameter. It was concluded that measurements of tangential core diameter would provide a reliable method to compare growth stress levels in different groups of trees.

Several workers attempted to develop mathematical models to predict growth stress distributions over the cross-sections of both vertical and leaning tree stems.

By integrating a curve illustrating the progressive longitudinal compression of the core of a tree published by Jacobs (1945). Boyd (1950, Part I) derived an expression giving the longitudinal stress that theoretically exists at any point in the cross-section of the vertical stem:

$$Y_1 = 0{,}02555 \, (r_o^{\,0{,}075} - r_1^{\,0{,}075}) + t_o$$

where: r_o represents the outside radius of the stem (inches)

r_1 represents the distance from the pith to the point for which a strain value is required (inches)

t_o represents the tensile strain initially developing in each new sheath of cells.

y_1 is the longitudinal strain theoretically existing at radius r_1

However, Boyd stressed that the longitudinal strain existing at any radial point given by the expression above, is purely theoretical because the immediately recoverable longitudinal strain will be less than that given by the expression, because of plastc relaxation of stress, the degree of which would depend on the level of stress and duration of load.

Kübler (1959, Part 2) developed a similar model for longitudinal stress distribution. His model was based on the assumption that initial stress in each sheath of newly formed cells added to the periphery of the stem is constant and that the elasticity of stem is transversely isotropic:

$$\sigma = \sigma_a(1 + 2 \ln r/r_a)$$

where σ is the longitudinal growth stress at any radius from the pith in the stem

σ_a is the longitudinal growth stress of the newest wood of the tree

r_a is the outer radius of the tree

Gillis (1973) analysed internal stresses resulting from peripheral growth stresses by treating the stem as a linearly elastic, isotropic and homogeneous, three-dimensional continuum. His results showed good agreement with the results obtained by Kübler.

Archer and Byrnes (1974) and Beck (1974) developed longitudinal growth stress distribution models that relaxed the condition of isotropy. These workers found Kübler's model to be a good approximation of their cylindrically orthotropic models for longitudinal growth stress distribution (as reported by Post, 1979).

Post (1979), in reviewing existing longitudinal growth stress models, stressed that all models developed fail to accuraltely model the longitudinal growth stress distribution in trees in several important ways, namely:

1) They predict comprehensive compressive longitudinal stresses near the centre of trees that are far greater than the longitudinal compressive strength of wood.

2) They consider the modulus of elasticity of the wood in a cross-section of a tree to be constant. It is well established that the modulus of elasticity varies with radial position in the tree.

3) They consider the modulus of elasticity to be independent of time and stress intensity. It is well established that wood exhibits creep and relaxation as well as a non-linear stress-strain relation above its proportional limit.

4) They consider the growth stress in each new layer added to the stem to be constant regardless of the age and diameter of the tree.

Post (1979) developed a new, more flexible model which can simultaneously utilize non-linear and time-dependent stress-strain relations, varying growth stresses in the newest wood of the tree, and varying properties of the wood from pith to the bark, in making predictions of the longitudinal growth stress distribution in a tree stem.

Post's model predicted longitudinal growth stress distribution very similar to those predicted by the models developed by Kübler (1959, Part 2) and Archer and Byrnes (1974). However, by using the non-linear stress relation, Post's model predicted much lower stresses towards the centre of the tree which are within reasonable limits of the compressive strength of wood (Figure 4.3).

4.5 Control of end-splitting

Various techniques for reducing level of growth stress have been proposed over the past number of years and were reviewed by Malan (1979b). Most of these techniques were based on creep occurring within the log (Nicholson, 1970). Although many of the techniques resulted in stress relief of varying degrees, all these techniques are highly impractical and uneconomical, particularly under South African conditions.

The successful treatment of standing trees to reduce splitting in logs when these trees are felled and cross-cut into logs, has been reported by several research workers. Investigations by Giordano, Currõ and Ghisi (1969), and Giordano and Currõ (1972) have shown that internal stresses in Eucalypt trees could be reduced by girdling right through the sapwood at the base of the stem and leaving the tree standing for a few months. Girdling was found ineffective in reducing splitting in Hickory while leaf seasoning (biological drying) appeared to have a very slight effect (Smith, unpublished report, as reported by Goebel *et al.*, 1960). In South Africa, biological drying of debarked *Eucalyptus grandis* resulted in no reduction in splitting (Stubbings, 1973).

Although killing a tree and leaving it standing for a period of time proved to be a useful technique to reduce end-splitting in logs, the period necessary to get a significant effect on the degree of end-splitting might give rise to certain other problems under South African conditions. Serious degrade of the wood takes place as a result of surface drying and attacks by wood destroying insects such as pinhole borers, powder post beetles and particularly *Phorocantha semipunctata* (de Villiers, 1973; Malan, 1979a).

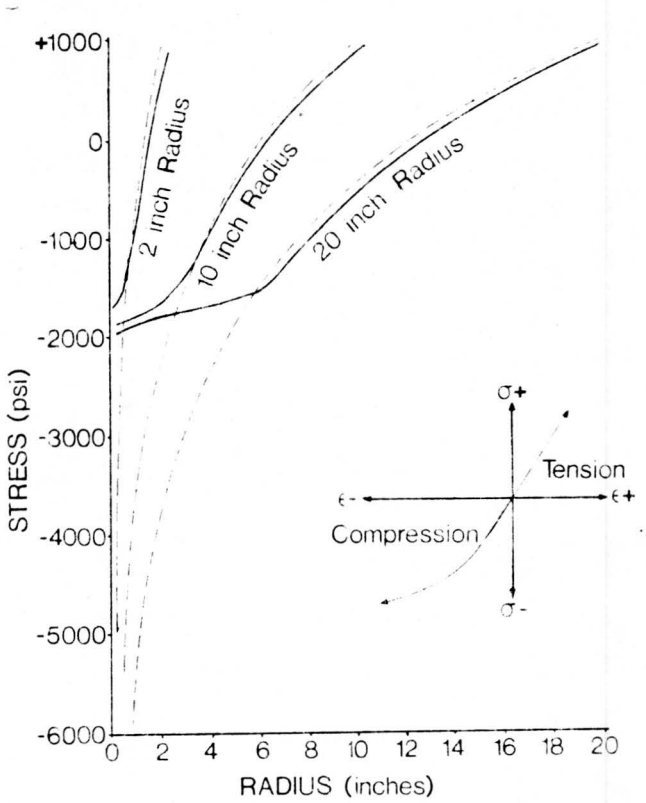

Figure 4.3:- Longitudinal growth stress distribution predicted by Post's model (solid line) and Kübler's model (broken line)(after Post, 1979).

Nicholson (1973a) found no reduction in growth stress levels in girdled *Eucalyptus regnans* trees after a period of 276 days. He noted, however, that a girdled tree, that was still alive after 276 days, showed a considerable reduction in stresses, compared to the other trees. Waugh (1977) investigated this phenomenon further by treating standing trees with defoliant spray for the purpose of holding the tree in a state of checked growth over a period of twelve months. Results indicated that peripheral strain can be reduced up to 20 per cent without the occurrence of degrade normally associated with dead standing trees.

Little is known about the relationship between felling damage end-splitting due to the presence of high growth stress levels. It is believed, however, that felling damage in the form of felling shakes or minute internal fractures reduces the ability of the log's end face to resist the deformation caused by the release of longitudinal stresses with the result that splits develop more rapidly and seriously at the log ends (Barnacle, 1970 and 1973).

Studies by Barnacle and Necesaný (1972) revealed a close association between felling damage and the occurrence of ring shake in logs. Although little is known about felling damage caused by impact during felling, precautions such as the following should be taken to reduce impact: (1) Felling the tree in the direction where the softest fall would result rather than in the direction of its lean and at the same time avoiding trees, logs or other objects lying on the ground; or, (2) using sophisticated machinery and equipment to reduce felling damage during the felling of large valuable timber, as described by Belozerov, Goldberg and Orlov (1960), Altman (1966), Johnstone (1968), McIntosh and Kerbes (1969) and Conway (1969).

Investigations by Barnacle and Gottstein (1968) and Giordano and Currõ (1972) have shown that end-splitting can be reduced considerably by cutting a circumferential groove with a chain saw on either side of the position of cross-cutting for log making. This technique can also be applied before felling by cutting a groove above the position where the tree is to be felled.

Field studies by van Wyk (1978) have shown that for South African grown Eucalypts, a groove of 25 to 40mm deep and a distance of one-third of the diameter at the cross-cut position from the position where the cross-cut is to be made, will redistribute the stresses at the cross-cut face and delay log splitting. The technique has proved to be quite effective, provided that the logs are sawn up within 30 hours, as the effectiveness of the grooves diminishes rapidly after that period. Similar studies by Malan (1979a) on mature *Eucalyptus grandis* confirmed the effectiveness of this technique but disagreed as regards the period of end-splitting delay. Results showed that the initial significant effect of the circumferential grooves is maintained for at least ten days after cross-cutting.

Conradie (1980) investigated the effectiveness of three groove depths and three distances from the cross-cut positions, giving nine treatment combinations. All treatments but one, namely the shallowest groove cut at the shortest distance, had a significant effect in reducing the amount of end-splitting compared to the untreated control logs. An analysis of variance revealed a highly significant interaction between groove depth and distance from the cross-cut point on the amount of splitting.

Apart from the fact that the effectiveness of the groove increased as the groove depth increased, a curvilinear relationship between groove distance and splitting was observed for each groove depth. In other words, for each depth the amount of splitting decreased as the distance from the cross-cut point increased up to a point whereafter distance from the cross-cut point lost its effect at an increasing rate. The inflection points varied in relation to the depth of cut. In the case of the groove cut to a depth of 1/6 of the radius, the maximum effect appeared to be at a distance of approximately one diameter from the cross-cut point, while those cut to a depth of 1/3 and 1/2 the radius, showed their maximum effect at a distance of 0,8 and 0,6 diameter respectively. At these turning points the amount of splitting was reduced to only 61,5 per cent, 31,5 per cent and 16,5 per cent respectively compared to the splitting that occurred in the control logs.

Investigations on the effect of non-axisymmetric cuts on the stress pattern in logs have shown that there are some acceptable angles of oblique cut that reduce stresses near the pith and thus cracking in the exposed log end (Tantichaiboriboon and Cook, 1977 Part I). A second paper by the same authors (1977, Part II) reported the most effective cut geometry if cuts (in addition to the original cross-cut) are permitted on only the log end, or on only the sides, or on both end and sides.They also investigated the best cut geometry when banding pressure is applied. Results have shown that some combinationsof radial pressure, and the extent over which it is applied, remove the highly stressed wood present in a plane cross-cut. It was also shown that splitting may be reduced by making cuts of special shapes, cuts made on the log end face being superior to those made on the side face or those made on the end and side faces simultaneously.

Restraining end-split development by using metal bands at the points where cross-cuts are to be made, or gang nails or S-hooks immediately after the cross-cut has been made, have been investigated (Tisseverasinghe, 1967; Mayer-Wegelin, 1955). These do not reduce stresses but they keep the log ends intact until some drying out increases the transverse tensile strength and balances some of the internal stresses (Mayer-Wegelin, 1955). In South Africa, attempts to reduce splitting in sawlogs by banding, were unsuccessful. As the metal bands have to be removed before sawing up the logs, splits develop during sawing in the usual manner (Scott, 1950; de Villiers, 1973). This problem was resently solved by using PVC rings to restrain end-split development (Wood Southern Africa, 1984).

Split development following cross-cutting progresses rapidly in the first three days reaching close to maximum values on the third day (Malan, 1979a). However, split development may continue in some logs for a considerable period of time afterwards (Priest *et al.*, 1982). Log length has no effect on the extent of log end-splitting within the normal range of log lengths used by the sawmilling industry (Priest *et al.*, 1982). In terms of yield recovery and to ensure the production of suitable quantities of timber of required dimensions, it is

recommendable that logs are prepared to the longest possible lengths which can be handled by extraction equipment, transport and the sawmill (de Villiers, 1973; van Wyk, 1978). Conversion should also take place as soon as possible after felling and log preparation (Priest *et al.*, 1982).

In the case of poles, de Villiers (1973) recommends shade drying for the first six to eight weeks after felling. Beyond the butt and the top end of the pole length, a collar of bark of 300mm should be retained. At the end of the drying period, each end of the pole is tightly banded and then cross-cut to the final length. This method of pole preparation reduces rapid drying at the ends, which would aggravate end-splitting, while rapid drying of the debarked part of the pole would lead to the development of surface checking. This would relieve circumferential tensile stresses in the debarked portion to a certain extent.

Both Barnacle (1971) and Imam and Heikal (1972) have shown that drying stresses interact with the release of growth stresses to produce radial splits at log ends. It was found that under severe drying conditions drying stresses can influence the initiation of cracks in collapse susceptible Eucalyptus in less than 20 minutes after cross-cutting has taken place (Barnacle, 1971). End-coating immediately after cross-cutting was therefore recommended to reduce splitting in such cases.

Other methods of reducing end-splitting in logs have also been reported. These are: drilling of holes in the centre of a log (Meyer-Wegelin and Mammon, 1954), the steaming or heating of logs in a clamped state (Cuznetov, 1950; Strikha, 1954; Platon, 1959; Kübler, 1959 Part 3; Skolmen, 1967), the storing of de-barked logs under manure for a period of several months (Giordano and Currõ, 1973), the storing of logs in water (Bryant, 1973 unpublished, reported by Edwards, 1973; Imam and Heikal, 1972).

Log conversion and seasoning

Splits in log ends cause serious reduction in conversion efficiency when logs are sawn into boards. Stress relief during conversion cause cut pieces to warp excessively resulting in further yield losses and a reduction in timber dimensions.

The sawing up of highly stressed logs with a single-bladed saw with a log carriage is not recommended. Because of the presence of growth stresses, the portion remaining on the carriage after removal of the first slab develops a convex bend. Consequently the subsequent boards sawn from this portion will vary in thickness along the length (de Villiers, 1973). This phenomenon has been demonstrated by Jacobs (1938, 1939, 1945) and Boyd (1950 Part I).

Frame saws, double-log-edgers or any other machine capable of making symmetrically placed cuts with reference to the log's cross-section are recommended to cut high-stressed logs. Because stresses are relieved symmetrically and simultaneously, accurately sawn boards are produced (Scott, 1950; Boyd, 1950 Part II; Turnbull, 1965; Dinwoodie, 1966; de Villiers, 1973). A deal frame saw with the saw blades set in an arc so that the outer blades cut ahead of those in the centre of the frame, was found to produce an increased yield of 11 per cent over that of a deal frame saw with saw blades set in a straight line (Priest *et al.*, 1984).

Maeglin and Boone (1981) introduced the so-called Saw-Dry-Rip (S-D-R) concept for sawing and drying low and medium density hardwoods for structural timber. Logs are sawn through-and-through into flitches which are then lightly edged to enable full kiln use. After drying, the flitches are ripped into the required dimensions. The proposed method of sawing balances longitudinal growth stresses in the flitches, and the additional width of the flitches restrains the tendency to warp. Drying stresses developing during drying offset the longitudinal growth stresses and if high-temperature drying is used, the natural

cellular bonding substance, lignin, plasticizes allowing the stressed to fibres slip and relieve the growth stresses from the wood. Results of tests carried out with several hardwood species indicated a considerable reduction in warp compared to conventional methods of sawing and drying.

During seasoning, splits rarely extend more than 200mm. Splits in boards originating from the other parts of the stem may even close up during seasoning (Priest *et al.*, 1984). Some researchers feel that boards should not be dried unedged because the edger removes the outer parts where the highest tensile stress exists (van Wyk, 1978). Unfortunately, a certain proportion of edged boards will develop end-splits and spring during seasoning, requiring trimming and edging again afterwards. On the other hand, by seasoning the unedged and untrimmed boards first, a certain amount of kiln space is wasted, and there appears to be a lower total yield of sawn timber, although handling costs are lower (de Villiers, 1973).

It is clear that the various attempts to reduce the degree of splitting have met with limited success. Some methods are simply not effective enough while the more promising techniques may be too expensive for practical implimentation, except in cases where very valuable logs are concerned.

Under South African conditions the following suggestions might help to get the most out of existing raw material. In the case of poles, the recommendations laid down by de Villiers (1973) should produce positive results if carefully followed. As far as the production of saw timber is concerned, the avoidance of unnecessary impact damage during felling, extraction, transport and sawing operations, the sawing up of the logs in the longest possible lengths with a frame saw or double-log edger in combination with other machines, preferably within 24 hours of felling and log preparation and slow seasoning (preferably under cover), should result in better sawn yields.

4.6 Growth stress - wood property relationships in tension wood

4.6.1 General

Growth stresses occur in both hardwoods and softwoods, but they are particularly severe in a number of hardwoods, especially Eucalypts. In non-leaning straight trees these stresses are fairly uniform in magnitude around the circumference of the stem. A tree whose vertical position has been displaced as a result of the action of some external force, or whose immediate environment has changed to such an extent that it no longer enjoys the most optimum crown position, will endeavour to change its crown position to the most optimum position in relation to its environment. In hardwood stems this is achieved by increasing the stress levels on the side of the stem where a pulling effect is needed, causing an asymmetrical peripheral stress pattern that is closely related to the needs of the stem for mechanical support (Nicholson *et al.*, 1975).

Since only the differentiating cells can respond to an external stimulus, the alteration of the longitudinal stress within these cells would be the most effective mechanism for controlling the movement of the stem and the crown (Nicholson *et al.*, 1973b). In extreme cases the process is characterised by the development of special tissue , known as reaction wood, on the "upper" side of the lean. Reaction wood, which is characterised by abnormally high growth stress levels, exhibits physical, chemical and anatomical properties which clearly distinguish it from normal wood (Scurfield, 1973; Manwiller, 1967; Princes Risborough Laboratory, 1972; Dadswell and Wardrop, 1949, 1955 and 1956; Perem, 1964; Dadswell, Wardrop and Watson, 1964).

4.6.2 Macroscopic characteristics of tension wood

Tension wood in hardwoods is not always as conspicuous as compression wood in softwoods. It forms on the "upper" side of the leaning stem and is often associated with eccentric growth. Although the presence of tension wood can be suspected in any tree that is out of the vertical, its presence is by no means

confined to leaning trees. It quite often occurs in trees of poor form or in the inner side of a tree with a straight bole. In the latter case such tension wood is being formed in the early stages of tree growth when it was susceptible to various external forces (Dadswell and Wardrop, 1956).

Tension wood can occur as definite bands which are much darker in colour, denser and harder than the normal wood. In many other species, especially those growing in tropical forests, tension wood is very difficult to detect on cross-cut faces. In these cases its presence is usually revealed by the extreme wooliness of the sawn and veneer faces (Dadswell and Wardrop, 1949). Sawn boards and veneer sheets also tend to distort and buckle on drying. This is mainly due to the abnormally high longitudinal shrinkage of tension wood. In a number of species tension wood shows up as a silvery zone rather more lustrous than the remainder of the surface on a clearly cross-cut section (Clarke, 1937).

In severe cases the presence of tension wood causes serious machining and finishing difficulties. Sawing and other machining operations have to be slowed down and saws and cutters tend to blunt faster. The quality of the machined surface is usually inferior (Princess Risborough Laboratories, 1972).

The problems with sawing, seasoning, machining and pulping of tension wood have been discussed by various authors, like Wahlgren (1957), Barefoot (1965), Perem (1964) and Koch and Hamilton (1968).

Longitudinal shrinkage of tension wood is considerably higher (sometimes up to 5 times) than for normal wood. This appears to be well related to the percentage gelatinous fibres present (Perem, 1964). The equilibrium moisture content seems to be slightly higher.

Both volumetric shrinkage (Perem, 1964) and radial shrinkage (Arganbright *et al.*, 1970) is less in tension wood than normal wood. Compared to non-leaning trees, radial shrinkage appears to be less on both the upper and lower side of leaning trees (Arganbright *ibid.*).

Studies carried out by Perem (1964) on the mechanical properties of tension wood indicated the maximum crushing strength, modulus of rupture, stress at proportional limit and modulus of elasticity to be significantly lower. On the other hand, toughness was decidedly superior to normal wood, particularly in the green condition. This could possibly be explained by the reduced volume of greater microfibrillar angles of the S1- and S2-layers as well as the poor bonding between the gelatinous layer and the rest of the seconday wall. Tension wood generally tends to be 5 to 30 per cent higher in density. However, Perem (1964) illustrated some cases where no density difference could be detected between tension and normal wood. Basswood showed a significantly lower density for tension wood than for normal wood. Studies by Taylor (1973) indicated no significant difference in specific gravity between the longest and the shortest radii of South African *Eucalyptus grandis* trees.

4.6.3. Microscopic characteristics of tension wood

One of the most reliable methods for the positive identification of tension wood is by microscopic examination. Wood fibres of tension wood are characterised by a thick inner layer known as the gelatinous layer which gives a cellulose reaction with appropriate stains instead of the normal lignin reaction. Of the various stains suitable for this purpose, safranin followed by fast or light green has become the most commonly used. The unlignified walls of tension wood fibres stain green, while the lignified parts display the red colour of the safranin.

The gelatinous layer often appears to be buckled and swollen, and partly detached from the secondary wall layer beneath. It sometimes completely fills the cell lumen and appears as a

jelly-like mass (Dadswell and Wardrop, 1949). The tearing away of the gelatinous layer from the rest of the secondary wall is apparently caused by microtome sectioning, when the gelatinous layer is not thick enough to withstand the pressure of the knife at the moment of cutting (Perem, 1964). It may also arise from other causes, such as growth stress relief (Chafe, 1977).

Studies, using techniques such as polarization optics, X-ray diffraction and electron microscopy, have shown marked differences in microfibrillar orientation of normal and tension wood (Dadswell and Wardrop, 1956; Manwiller, 1967). In normal wood the microfibrils in the S1- and S3-layers of the secondary wall have an average microfibrillar angle that is quite large with respect to the cell axis while that of the thick S2-layer is small. In tension wood the microfibrillar angle of the S2-layer is greatly increased and thus imparts a longitudinal component of shrinkage to the wood that is correspondingly large (Panshin and de Zeeuw, 1980; Norberg and Meier, 1966).

The gelatinous layer is highly crystalline with the microfibrils closely packed and orientated almost parallel to the cell axis. It is more refractory to light than the rest of the cell wall and often appears as a clear gel that nearly fills the cavity of the cell.

The gelatinous layer may occur as an "extra" layer to the normal structure, but quite often it occurs in the absence of the S3- or even both the S3- and S2-layers (Manwiller, 1967). Scurfield (1973) suggested that the layer structure of the cell wall of tension wood fibres depends on the stage of differentiation they have reached when the stem was displaced.

The presence of fibres having a gelatinous layer in the lumen or inside the secondary wall is commonly used as the sole criterion for the identification of tension wood (Hillis, 1978). The intensity of tension wood is usually related to the percentage of fibres containing the gelatinous layer. Such fibres often occur as small discrete groups within a matrix of normal fibres (Wilson and Archer, 1977).

Apart from the presence of the gelatinous layer, tension wood also differs with respect to other anatomical properties, i.e. vessels are less frequent and smaller in diameter, rays are smaller in size in some woods, axial parenchyma are small in size and amount, percentage fibres is distinctly greater, fibres have smaller diameters, are longer and contain fewer pits. Fibre walls are also thicker with somewhat more rounded outlines.

4.6.4 Chemical properties of tension wood

Priestly and Tong (1927) were among the first people who noticed that the wood on the tension side of tree stems remained unlignified, whereas the wood on the opposite side became lignified. These conclusions, which were mainly based on results of staining reactions, were later confirmed by chemical analyses carried out by Jayme *et al.* (1953), Wardrop and Dadswell (1948), Chow (1946) and Timell (1969).

Chemical analyses carried out by many researchers have consistently shown that tension wood contains more cellulose, less lignin, lower amounts of xylose residues and a slightly higher ash content than normal wood when the amounts are calculated as a percentage of the ovendry mass of the wood (Panshin and de Zeeuw, 1980). Lower pentosan contents were found in the tension wood of *Fagus sylvatica* (Chow, 1946) and *Eucalyptus goniocalyx* (Schwerin, 1938). On the basis of an assumed equal cellulose content, tension wood contains less glucomannan, two to five times as much galactan and the same, or slightly lesser amount of xylose (Timell, 1969). The galactan content is especially high in tension wood of certain genera, such as Betula, Eucalyptus and Fagus.

The gelatinous layer contains more than 98 per cent cellulose with only small amounts of other polysaccharides present (Furuya, Takahastu and Miyazaki, 1970; Norberg and Meier, 1966), causing a considerable increase in the cellulose content of tension wood. Increases varying from 40 to 50 per cent over that of normal wood, depending on the thickness of the layer and the proportion of fibres containing the gelatinous layer, have been reported (Panshin and de Zeeuw, 1980).

Wardop and Dadswell (1948) and Furuya *et al.* (1970) found the gelatinous layer to give a positive reaction for pectin with ruthenium red, a reagent thought two be specific for this polysaccharide. It was later found that this reagent not only stains pectin, but all polysaccharides containing carboxyl groups. Mia (1968) claimed that the gelatinous layer contains non-cellulosic polysaccharides, but Timell (1969) later critized this finding since several researchers have shown that the gelatinous layer is lamellar.

In a study by Schwerin (1958) on *Eucalyptus goniocalyx* it was found that water soluble non-resistant polysaccharides of tension wood were liberated much more readily by methanol at 150°C than those from normal wood. Normal wood seems to contain little or no galactose in its non-cellulosic polysaccharides, while those of reaction wood contain considerable quantities of galactose. After methanol extraction about 25 per cent of the galactose remained in the α-cellulose.

Tension wood fibres contain less lignin than normal wood when expressed as a percentage of the total wood. However, the portion of the secondary wall, formed prior to the development of the gelatinous layer contains as much lignin and xylose as normal wood, suggesting that the lack of lignification in tension wood fibres should not be regarded as a characteristic of tension wood as a whole, but only of the gelatinous layer (Timell, 1969).

Investigations by Bland (1958 Part I and II, 1961) on tension wood of Eucalyptus and other Australian hardwoods showed that lignin in tension wood differed in its ultraviolet spectra from that of normal wood, but syringylaldehyde and vanillin occurred in the same ratio and yield as in normal wood on oxidation with nitrobenzene and alkali. The lignin yield from *Eucalyptus goniocalyx* tension wood was found to be very low and the lignin was too soluble to reprecipitate in the solvent employed for purification. Bland (1961) concluded that tension wood lignin does not differ from that in normal wood, except that it is more closely bound to the polysaccharide framework.

Investigations on Beech (*Fagus sylvatica*) indicated that the methoxyl content of tension wood is significantly lower than that of normal wood, but the methoxyl content of the isolated lignin was found to be virtually the same in both types of wood (Chow, 1946). In *Eucalyptus goniocalyx* the lignin of tension wood was found to be more resistant to methanol extraction than that of the other zones (Schwerin, 1958).

Reaction wood was found to have a lower extractive content than normal wood. It is maintained that the darker colour of reaction wood is the result of its lower extractive content (Dadswell and Hillis, 1962). On the other hand, studies on Beech indicated tension wood to have a higher hot and cold water solubility, while the alcohol-benzene solubility was found not to differ significantly (Chow, 1946).

4.7 Growth stress - wood property relationships in normal wood

In leaning trees there is a gradation of peripheral growth stress around the stem, with maximum values in the vicinity of tension wood formation, i.e. the upper side of the lean (Nicholson *et al.*, 1975; Trenard and Gueneau, 1975). From the previous section it is evident that the special features exhibited by the extreme tissue of tension wood, which often occur on the "high-stressed" side of leaning stems, have been studied extensively in many tree species.

Attempts have also been made to study the relationship between level of longitudinal stress and fibre structure and various properties of normal wood. Close relationships were observed (Nicholson *et al.*, 1972 and 1975). Volumetric shrinkage, basic density, proportion of thick-walled fibre cells and modulus of elasticity increased and percentage Klasθn lignin decreased with an increase in peripheral growth stress. From these results it was concluded that those wood characteristics normally associated with high-stressed tension wood are only "extreme" forms and that the degree to which tension-wood-like features are present at any particular point in the stem is in fact a reflection of the intensity of growth stress at that point.

Nicholson (1973b) suggested that a tree, in order to maintain its vertical orientation or to change its spatial position in relation to neighbouring trees, would only be able to achieve this by changing the stress within the stem at positions where required. The strong correlation found between the number and degree of thick-walled fibre cells and level of longitudinal stress, lead to the conclusion that the periodic differentiation of thick-walled fibre cells is the basic mechanism used by the tree to regulate longitudinal growth stress (Nicholson, 1973b; Nicholson *et al.*, 1975). It can then be concluded that tension wood development is simply a maximum development of the same longitudinal shrinkage of fibres which generates growth stresses in "normal" wood and that no clear demarcation in fact exists between tension wood and normal wood. Since several physical properties are determined by the number and degree of thick-walled fibre cells present, it explains why these properties also vary with the level of longitudinal growth stress.

While much of the variation in wood properties within trees might well be explained by these relationships, it might be hypothesized that between-tree differences in wood properties may also be explained by these relationships, for growth stress intensity has been found to vary considerably from tree to tree. Limited studies have been carried out in this regard.

Studies on non-leaning Hickory (*Carya spp.*) trees have indicated that internal growth stresses are greater in stems that contain large amounts of gelatinous fibres than in stems in which the concentration of such fibres is not high. As a consequence, it was concluded that the degree of log end-splitting would be related to the proportion of gelatinous fibres present (Anon. 1956, as reported by Perem, 1964). Goebel *et al.* (1960) obtained similar results, but their study (also on Hickory) further suggested that the distribution pattern of tension wood in severely split trees might be somewhat different from that encountered in non-split trees. Their study revealed that in the case of a severely split non-leaning tree gelatinous fibres

would be found in relatively large amounts over the entire cross section of the stem at all heights except the stump. The two non-split trees that were examined (one which leaned and the other not) showed the typical distribution of gelatinous fibres one would expect to find in a leaning tree.

Microscopical examinations of the xylem of non-leaning *Eucalyptus regnans* trees containing high growth stress levels revealed the presence of radial dislocations in the secondary wall of a large proportion of the fibres (Chafe, 1977). These were characterised by a localised disruption in the microfibrillar orientation of the cellulose and occurred in both lignified and unlignified cell walls. These features could not be found in trees having low peripheral growth stress levels. This suggested that these features originated from the longitudinal contraction and a corresponding transverse expension of the cell wall as a consequence of the stress relief taking place during the removal of the sample from the stem. The author also speculated that the irregular or wavy form of the inner border of the gelatinous layer of the secondary wall does not represent a sequential stage in wall formation as suggested by Scurfield and Wardrop (1962), but that it arises as a result of the stress relief that takes place when the sample is removed from a highly stressed tree.

Apart from studies by Goebel *et al.*, (1960) and Chafe (1977) no known effort has been made to study the wood properties of high-stressed trees as opposed to low-stressed trees.

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PART II

EXPERIMENTAL WORK

CHAPTER FIVE

OBJECTIVES OF STUDY

Eucalypt trees are characterised by an enormous between-tree variation in the degree of splitting, even between trees growing within the same general environment. Malan (1979a) observed slight but definite site and seasonal influences on the amount of log end-splitting as well as marked differences between geographical regions. Findings of a similar nature were also reported by Okuyama *et al.* (1981) and Bielczyk (1953). In *Eucalyptus regnans* the variation in mean level of longitudinal stress on the stem periphery could not be explained adequately in terms of environmental factors such as wind exposure, rate of growth, stand density, site and elevation (Nicholson, 1973b).

The general lack of association between environmental factors and mean stress levels in individual trees, had led to the generally agreed conclusion that the mean level of stress in a tree is primarily controlled by the genetic make-up of the tree. In both Poplar (Waugh, 1972) and *Eucalyptus grandis* (Malan, 1979a) a significant genetic effect could be proved but due to the lack of suitable genetic material, a precise quantification of the genetic effect could not be obtained.

Existing evidence indicates that stress levels in individual trees are both controlled by factors of environment and genetics. However, in both these fields information is limited and in certain cases somewhat subjective, and should by no means be regarded as conclusive. In the case of South African grown *Eucalyptus grandis* this type of information is virtually non-existent.

In this study an attempt was made to explain more precisely the variation in growth stresses in plantation grown *Eucalyptus grandis* trees. A knowledge of this nature would indicate to what extent stress levels can be modified using either genetic or environmental methods of improvement. It would thus enable silviculturalists and tree breeders to develop more efficient improvement programmes aimed at reducing the levels of stress in trees of future generations of this species, and may be even in existing plantations.

In the first instance a detailed study was conducted to investigate the relationship between factors of environment and the degree of log end-splitting. This study was based on the argument that the micro-environment within a stand varies from tree-to-tree in spite of the general aim of management to maintain stand uniformity through silvicultural practices. As a result of the inevitable lack of stand uniformity, growing space for crowns, and availability of light, soil moisture and nutrients will vary from tree to tree. This would in particular cause marked differences in crown size and exposure to wind induced drag forces.

This variability in growth conditions would undoubtedly produce major modifications in the characteristics of the wood formed among individual trees, and presumably also in the level of stress generated in the tree.

It was envisaged that these differences in growth conditions might explain some of the variation in stress levels found among plantation grown trees. Since environmental factors are, by their nature, very difficult to measure accurately, various tree and crown characteristics known to be the most responsive to environmental influences, have been used as an indirect measure of environment. This was considered adequate in view of the magnitude of stress variation present. Due to the large number of trees sampled for this study, the determination of stress levels

in each individual tree could not be considered. The amount of end-splitting in logs, assessed at various heights in the stem, was alternatively used as an indirect measure of stress in each tree.

Since there is sufficient evidence to believe that a significant proportion of the between-tree variation in growth stress is controlled genetically, an attempt was also made to obtain a more accurate estimate of the genetic effect. Several well designed full-sib and seedling progeny trials have been established since 1975, thus providing suitable material to determine the genetic component. Results of this study are reported in Chapter seven.

In the third instance an attempt was made to investigate the relationship between stress level in normal vertical trees and the properties of the wood.

It is commonly known that in leaning hardwood trees there is a gradation of stress levels around the stem with the maximum values in the vicinity of the opposite side of the lean. Wood formed under conditions of extreme tensile stress (commonly referred to as tension wood) has been studied extensively and in great detail by several research workers. The properties of this extreme tissue type, as opposed to those of normal wood, have already been discussed in Chapter four.

However, studies on leaning *Eucalyptus regnans* trees have indicated that no clear demarcation is apparent between "normal" and "tension" wood. The variation in peripheral stresses as a result of the lean was found to be associated with changes in the basic anatomical and chemical properties of the wood, in other words, the transition from normal wood to tension wood was found to be gradual.

While studies have been carried out to investigate the relationship between growth stress level and wood characteristics within leaning trees (Nicholson *et al.*, 1972), no known attempt

has been made to relate the level of stress in normal vertical growing Eucalypt trees to the properties of the wood.

In view of the close association found between stress level and wood properties within leaning trees, it can be hypothesized that in normal, non-leaning trees much of the variation in wood properties might be explained by these relationships, for growth stress levels have been shown to vary considerably between trees.

If such a relationship could be confirmed it would possibly help to bring about a better understanding of the large between-tree variation in wood properties characterising this species. A knowledge of these relationships would also be of considerable importance to determine which commercially important variables will be affected if the genetic and/or environmental manipulation of stress levels in individual trees prove to be a viable proposition. It might also enable the development of discriminant functions based on easily measurable variables which could be used to identify low-stressed individuals for selection in breeding programmes. Furthermore, a study of juvenile-mature correlations of variables associated with growth stress might provide information regarding the possibility of early growth stress evaluation in, for instance, progeny and provenance material.

Investigation of the above mentioned relationships, their significance from a utilization point of view, and their practical value in a tree breeding programme are discussed in Chapter eight.

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CHAPTER SIX

INVESTIGATION INTO THE EFFECT OF ENVIRONMENT ON THE LEVEL OF GROWTH STRESS IN THE STEMS OF *EUCALYPTUS GRANDIS*.

6.1 Introduction

Studies on end-splitting in South African *Eucalyptus grandis* trees have revealed considerable differences associated with geographical area and season (Malan, 1979a). However, marked differences were also found between trees growing under apparently uniform site conditions. The logical inference which can be drawn from this is that variation in log-end splitting is related to both environmental and genetic factors.

Nicholson (1971b and 1973b) observed a similar variation in *Eucalyptus regnans*. Attempts were made to determine to what extent the observed variation in this species could be explained in terms of environmental factors. Results obtained from a limited number of trees indicated that the mean level of peripheral growth stress varies independently of both growth rate and environmental factors such as exposure to wind, stand density, site and elevation. Thus it was concluded that the level of growth stress in a tree may be mainly controlled by genetic factors.

No known attempt has been made to establish to what extent the observed variation among *Eucalyptus grandis* trees growing within the same general environment can be explained in terms of the differences in growing space that normally exists among plantation grown trees.

Although thinning regimes aim to maintain uniformity in spacing among the residual trees in general, existing thinning practices do not accomplish absolute spacing uniformity throughout the life

of a stand. From fairly early in the life of a stand a between-tree variation will exist in growing space for the crowns and particularly exposure to lateral wind forces and light, and the availability of soil moisture and nutrients.

As a result of the periodic opening-up of a stand through thinning and tree deaths, the remaining trees immediately respond to their new environments in an increased diameter increment, changes in crown size and form and sometimes in stem form, and changes in wood properties. This period of vigorous growth and accompanying changes will continue until full competition is again established. As a result of the unavoidable uneven opening-up of the stand for reasons already explained, the duration of vigorous growth and associated changes following each thinning, and the extent to which it is taking place, will vary from tree to tree.

After the final thinning, each of the remaining trees again respond as previously explained, by developing in such a way as to maintain themselves optimally in their respective immediate environments. Soon trees will be in equilibrium with the normal factors of environment, a situation that normally persists until clearfelling 10 to 25 years later.

The main function of the tree stem is that of mechanical support and to serve as a conductive link between the roots system and leaves. Stem development is the result of two meristems, the apical meristem which activity if primarily responsible for height growth and a lateral meristem known as the vascular cambium, which is responsible for the production of new secondary xylem tissue. The activities of these meristems are controlled by various environmental and genetic factors and their interactions. The result of these influences on the meristems responsible for wood formation and height growth are chemical, physical and mechanical wood properties that vary within as well as between tree stems. The characteristics of the stem as well as the various properties of its secondary xylem is, therefore, the cumulative result of the activities of these meristems throughout the life of the tree.

It can be assumed that each tree will tend to develop to its fullest extent and will always attempt to attain complete equilibrium with the normal factors of environment. Crown development is directly influenced by the availability of light and indirectly by the physical structure and nutrient status of the soil; both affecting the photo-synthetic efficiency of the crown. The crown is, therefore, the most important receptor of environmental influences, and since the crown acts as a centre where wood formation is regulated, changes to the crown will undoutbtedly produce modifications in the characteristics of the wood formed.

Due to the large surface area of crown in relation to the stem, mainly as a result of the high area-mass ratio of the leaves, the influence of external forces, mainly wind, will also play an important role in the development of each tree. The influence of wind in a stand on individual trees, is determined by many factors. The effect on isolated and edge trees will be different and to a greater extent than on trees within a stand (Fraser, 1963). Wind influences will also be affected by the tree's height in relation to that of his neighbours, in other words, the degree of protection provided by neighbouring trees.

Fraser (1962) found crown mass to be the most important factor determining wind drag. His studies indicated that the effect of crown mass on drag was independant of branch density (compactness), but the situation can be different for trees in a stand (Hall, 1967).

For a rigid body, the wind-induced drag force is proportional to the square of the wind speed. In the case of trees, the crowns become progressively more streamlined as the wind speed increases (Hall, 1967). Studies carried out by Sauer *et al.* (1951) and Fraser (1963) indicated a linear relationship between drag and wind velocity. At low speeds (below 18 knots), there was no direct relationship between drag and wind speed. At a wind velocity of 18 knots the branches have deformed to a more

streamlined shape and a regression equation was developed which showed that drag force is a function of crown mass.

In discussing wind speed profiles for open grown trees, Hall (1967) postulated that wind-induced bending moments decrease linearly with height from the ground to the base of the crown. Above this point the rate of decrease diminishes according to the proportional mass distribution of the crown.

In a forest stand, however, the action of wind forces on individual tree stems is more complex. It will depend on many factors which include, apart from those already mentioned, the height of the tree in relation to its neighbours and growing space. Whilst wind forces acting on a tree will result in an elliptical pattern of movement with the longest axis parallel to the wind direction, the pattern for a plantation grown tree must be irregular as a result of the gusty, turbulent nature of the wind in the forest (Hall, 1967).

Since one of the important functions in the stem is one of support, it can be postulated that the growth stresses developing in the stem in order to stabilize the tree, will to some extent be a function of the trees immediate environmental and of the external forces acting on the tree.

In the present study an attempt was made to determine to what extent the observed variation in growth stresses among plantation grown trees can be explained in terms of the environmental influences acting on the tree.

Many environmental factors act on a tree at any one time and they interact in various ways to ultimately produce patterns of crown growth (Larson, 1963). Because of the complexity to interpret the many environmental factors acting on a tree at any time, no attempt was made to determine which one, if any, is predominating.

Crown characteristics were considered as the nett result of environmental influences and used to serve as a indirect measure to assess the effect, if any, of the immediate environment. All crown characteristics considered are thought to be highly responsive to environmental influences. This approach was considered reliable enough in view of the magnitude of growth stress variation (as revealed by end-splitting in log ends), among plantation grown trees.

In addition, attempts were made to relate seasonal variation in end-splitting to seasonal variations in soil moisture content. Assessments were also made to study the effect of growth rate on split development as well as how log end-splitting varies with height in fast and slow grown trees.

6.2. Experimental procedure

The material used was obtained from two *Eucalyptus grandis* stands of similar age (twenty-one years at the start of the investigation), and of similar silvicultural background and stocking. These stands were selected on the Westfalia Estate in the Letaba district in the North-Eastern Transvaal. Since the stands were situated at a close distance from one another with very little difference in altitude, climatic effects related to temperature and rainfall experienced by these stands were assumed to have been virtually similar throughout the life of the trees.

However, the two stands differed considerably in site quality, as reflected by both mean tree diameter at breast height and mean tree height (Table 6.1), and thus provided a suitable basis to study the effect of rate of growth on stress intensity.

Random samples of ten trees were taken at monthly intervals from each site for 12 months, commencing in January 1980. After measuring the overbark diameter at breast height and the underbark width at the butt of the basal log to be, all sample trees were felled. The variables listed in Table 6.2 were accurately recorded and used in the statistical analyses.

Table 6.1:- Mean D.B.H. and Height of trees sampled in two stands of different soil qualities.

Soil Quality	Mean D.B.H. (mm)	Mean Tree Height (m)	Sample size
Good	431	39,1	120
Poor	361	31,9	120

Table 6.2:- List of measured and derived variables and their code names.

Measured variables		unit
X1	Overbark diameter at breast height (DBH)	mm
X2	Total tree height (TTH)	m
X3	Height to the first living branch (HLB)	m
X4	Number of branches in the lower half of the crown (BN)	-
X5	Average branch length of the branches in the lower half of the crown (ABL)	m
X6	Average branch thickness of the branches in the lower half of the crown (measured 100 mm from the base of the branch) (ABT)	mm
X7	Stem diameter one-quarter distance of the total crown length from the first living branch (SD)	mm
X8	Total rainfall for each month (MRF)	mm
X9	Mean monthly temperature (MNT)	°C
Derived variables		**unit**
X10	Crown percentage (X3/X2 X 100) (CP)	%
X11	Number of branches per metre (BNPM)	-
X12	Branch length-stem diameter ratio (X5/X7)(BLSD)	-
X13	Branch thickness-stem diameter ratio (X6/X7) (BTSD)	-
X14	Stability factor (X1/X2) (SF)	-
X15	Mean annual increment (X1/Felling age) (MAI)	mm
X16	Whole tree volume (under bark) (from X1, X2 and X17) (TV)	m^3
X17	Taper per metre (TM)	mm

Each tree was debarked and divided into 2.4 metre logs according to the pattern shown in Figure 6.1. Provision was made for the cutting of a 50mm stem disc between all adjacent logs and at the top of the upper log, giving a total number of five discs per tree. These discs were immediately sealed in plastic bags and taken to the laboratory for the determination of ovendry density. These disc samples were used to study wood density variation in trees of varying growth stress intensity (see Chapter eight).

Before cross-cutting, the girth at the butt and top end of each log was measured to the nearest millimeter at a distance of 20mm from the cross-cut point. The position of the girth tape was clearly marked around the entire circumference of the log at the position of measurement. The importance of this procedure will be explained later. After the initial girth measurements, the stems were cut into logs and discs and the logs left in the plantations for a period of 72 hours under semi-covered conditions to provide a time lapse for maximum end-splitting development.

The stems of the sampled trees were debarked simply to fit in with the normal plantation activities. Surface drying stresses were not considered a factor of significance taking into account the mild conditions the logs were subjected to in the plantations as well as the short time lapse between felling and the final measurement. No log handling took place during the three-day period to avoid split development as a result of externally induced stresses.

At the end of the three-day period all girth measurements were taken using the same girth tape as used for taking the first set of girth readings. In order to avoid serious errors due to the presence of surface irregularities, the second reading was taken exactly on the same circumferential line where the first reading had been taken.

The degree of end-splitting in each log was recorded as the percentage increase in girth as a result of the opening up of the

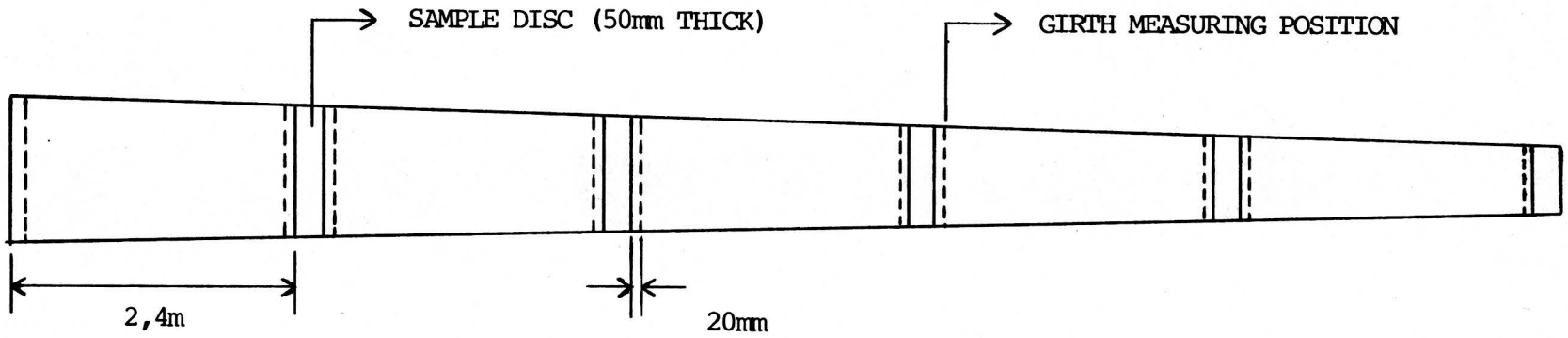

Figure 6.1:- Pattern of log and sample disc preparation.

log end due to the split development. The accuracy of this technique of assessing the degree of log end-splitting has already been investigated and found to be of suitable accuracy (Malan 1979a).

Because of the size of the experiment, the use of methods to determine stress levels from direct growth strain measurements could not be considered. However, studies on Australian *Eucalyptus regnans* indicated that an excellent correlation exists between the level of stress and the extent of log end-splitting (Nicholson 1971b). Full details of similar studies carried out in South Africa on *Eucalyptus grandis* are outlined in Appendix 1. As a result of these findings the degree of end-splitting was considered as a reasonable reliable and convenient indirect single measure of the stress level in the immediate vicinity of the cross-cut face, and presumably also for a fair part of the logs adjacent to the cross-cut position.

6.3. Statistical analyses

Since splitting measurements were carried out at six height levels and at monthly intervals for a period of twelve months on two separate sites, it was considered appropriate to test the statistical significance of these factors simultaneously using a three-way analysis of variance. Because all the percentage values for end-splitting were well below 10 per cent it could not be merely assumed that the individual percentages follow something close to a normal distribution with a homogeneous variance. Since normality is one of the fundamental underlying assumptions of the analysis of variance, it was necessary to correct for lack of normality by applying the arcsine (angular) transformation to the original data before performing the analysis (See: Sokal & Rohlf, 1969).

Because of the size of the experiment the data are presented in a summarized form in Table 6.3 giving only the mean of the ten readings for each factor combination. Since ten replicate trees were examined for each combination of factors, an estimate of the within subgroup variance could also be obtained.

Table 6.3:- Summary of log end-splitting from two stands of different site quality, for different heights above ground level and for different months. (Tabular values are averages of log end-splitting for ten trees.)

Site quality	Height in tree(m)	Average splitting (per cent)												
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN
GOOD	0,0	0,23	0,15	0,62	0,18	0,48	0,31	0,72	0,14	0,17	0,31	0,11	0,05	0,30
	2,4	0,26	0,38	0,48	0,63	1,75	0,50	0,60	0,55	0,54	0,66	0,49	0,28	0,59
	4,8	0,58	0,45	0,62	0,65	1,13	0,48	0,34	0,48	0,67	0,54	0,82	0,49	0,60
	7,2	0,79	0,29	0,73	0,87	0,59	0,58	0,46	0,40	0,66	0,48	0,48	0,47	0,57
	9,6	0,80	0,35	0,71	0,53	0,81	0,46	0,36	0,49	0,62	0,55	0,89	0,59	0,59
	12,0	0,57	0,19	0,64	0,44	0,75	0,58	0,54	0,68	0,59	0,29	0,60	0,52	0,51
	MEAN	0,53	0,30	0,63	0,54	0,88	0,48	0,50	0,46	0,54	0,47	0,57	0,40	0,52
POOR	0,0	0,40	0,25	0,02	0,00	0,24	0,19	0,14	0,14	0,06	0,00	0,11	0,04	0,10
	2,4	0,09	0,07	0,03	0,55	0,76	0,12	0,17	0,17	0,09	0,17	0,11	0,16	0,21
	4,8	0,32	0,16	0,11	0,74	0,32	0,06	0,17	0,24	0,13	0,17	0,33	0,30	0,25
	7,2	0,21	0,15	0,19	0,22	0,32	0,12	0,43	0,18	0,13	0,31	0,23	0,08	0,21
	9,6	0,17	0,11	0,08	0,13	0,12	0,11	0,16	0,17	0,15	0,20	0,30	0,53	0,18
	12,0	0,15	0,10	0,09	0,30	0,49	0,07	0,15	0,26	0,24	0,23	0,25	0,05	0,18
	MEAN	0,16	0,14	0,09	0,32	0,38	0,11	0,19	0,17	0,13	0,18	0,22	0,19	0,19

Since several measurements were made on each tree, advanced multivariate statistical techniques were used to study the relationship between average tree splitting and the tree variables selected for study. Preliminary tests were applied to all data to examine dispersion. All data but splitting was found to be normally distributed, thus no transformation was required.

6.4 Results and discussion

6.4.1 Analysis of Variance

The results of the analysis of variance are presented in Table 6.4. All three main factors were found to be statistically significant while none of the first order interactions or the second order interaction was found be to be significant at a 1 per cent or 5 percent level of probability.

6.4.1.1 Effect of site quality on level of growth stress

On average the trees from the good quality site developed more than twice as much splitting than those from the poor quality site (Table 6.3). Statistically this difference proved to be highly significant (Table 6.4). Since all other known factors were kept constant, this result suggests a highly significant effect of rate of growth on the level of growth stress.

Considerable difference in splitting occurred between trees within sites, even between adjacent trees. Although it is generally believed that fast-grown Eucalypts have a greater tendency to develop severe splitting, no correlation could be found between diameter increment and growth stress intensity (Hillis, 1978). If this also applies to South African *Eucalyptus grandis*, it means that all fast growing trees within a stand would not necessarily contain high levels of growth stress. This would suggest that selection for increased volume production and reduced level of stresses could be carried out simultaneously.

6.4.1.2 Effect of height in tree on splitting

As indicated by the analysis the effect of height on end-splitting was highly significant. Linear comparisons were carried out to measure the linear, quadratic and cubic effect of height above ground level on splitting. Higher order effects were not tested and were treated as a deviation from the qualified effects rather than as evidence for quartic and quintic effects. All three effects were found to be significant with the quadratic effect showing a particularly high F-ratio.

The effect of height above ground level on end-splitting is shown in Figure 6.2. On average, splitting was considerably higher at all height levels in trees from the better quality site, but the pattern of variations in the two samples appeared to be generally similar, *viz* a sharp increase in splitting in the first approximately 2.4 metres followed by a slight decrease with increasing height above ground level. These patterns were also very similar to that observed in previous studies on this species (Malan, 1979a). However, the present study revealed close to maximum splitting values at 2.4 metre height; a fact which could not be established previously due to the absence of measuring heights between ground level and 4 metre height.

The relationship between growth stress and height in tree has been studied by several other workers. Jacobs (as reported by Boyd, 1950 Part III) found no effect of height in tree on growth stress level, while Nicholson (1971a) reported only a small variation with height. Yao (1979) found a weak relationship between longitudinal growth stress and height above ground level for three North American hardwoods. He found peripheral growth stress increased to a height of 8 metre followed by a decrease to the final 11 metre height.

In South Africa, end-split studies on trees from different geographical area, revealed different patterns of variation (Malan, 1979a).

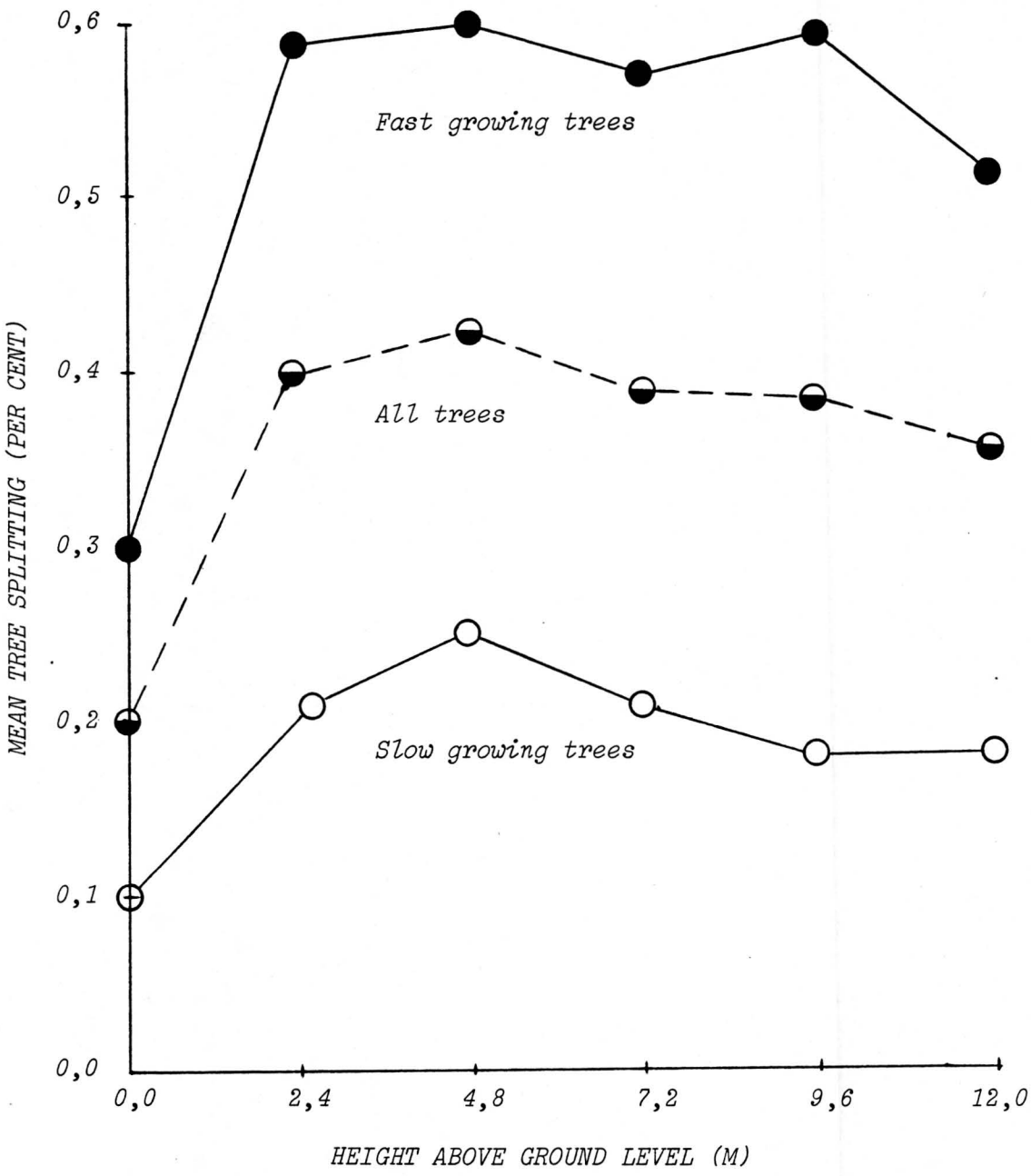

Figure 6.2:- Relationship between log end-splitting and height in tree.

Table 6.4:- Analysis of variance of arcsine transformed splitting data.

Source of variation	df	Sum of Squares	Mean Square	F-ratio
Sites	1	1079,41	1079,41	288,5**
Heights	5	340,29	68,06	18,2**
Linear	1	47,68	47,68	12,7**
Quadratic	1	262,88	262,88	70,3**
Cubic	1	24,87	24,87	6,6**
Residual	2	4,86	2,43	0,6ns
Months	11	245,53	22,32	5,9**
Sites x Heights	5	23,50	4,70	1,3ns
Sites x Months	11	67,70	6,15	1,6ns
Heights x Months	55	330,52	6,01	1,6ns
Sites x Months x Heights	55	202,91	3,69	0,9ns
Within subgroups (Error)	1296	4849,05	3,74	
Total	1439	7137,79		

** Significant at the 1 per level of probability.
ns Non-significant.

Recent studies by Chafe (1981) on Australian grown *Eucalyptus regnans* indicated increases in longitudinal growth strain and growth stress with height in tree but the trends were not found to be statistically significant. It was concluded that this might explain the greater tendency of logs in the upper part of the stem to split more.

6.4.1.3 Seasonal effect on log-end splitting

The effect of the time of the year of felling proved to be highly significant (Table 6.4). Trees from both sites showed a similar seasonal variation in splitting ($r = 0,59$, $p < 0,05$) (Figure 6.3). The amount of splitting remained on a fairly constant level through almost the entire year. However, in the autumn months April and especially May, the average amount of splitting was markedly higher.

As previously indicated, there is general agreement among foresters and sawmillers involved in Eucalypt wood production and processing of the existence of a seasonal variation in log end-splitting with the peak splitting period being early summer. These observations were in fact confirmed by a study conducted in the same area during 1977 (Malan, 1979a). The present study, however, showed a seasonal splitting pattern completely different from that found in 1977, which suggests that the pattern may fluctuate from year to year.

It was envisaged that the splitting patterns for the two periods concerned as well as the apparent inconsistency of the peak period with respect to time of the year, would best be explained by the weather patterns for those two particular periods. The possibility of a relationship between water stress and growth stress levels has already been dealt with in Chapter four.

To study this aspect, rainfall data as well as maximum and minimum temperature data for the Tzaneen area were obtained from the Weather Bureau in Pretoria for the two periods concerned (Table 6.5).

In this area the wet season generally starts in November and ends in March. Temperature rises sharply in September/October after the cool winter season which starts in May/June. Monthly soil moisture deficiencies for the periods March 1977 to April 1978 and January 1980 to December 1980 were estimated according to Thornthwaite and Mather's method (Thornthwaite and Mather, 1957). Monthly soil moisture deficiencies are given in Table 6.5.

In this method it is assumed that actual evapotranspiration is equal to potential evapotranspiration when precipitation is equal to or exceeds the potential evapotranspiration. When precipitation is less than the potential evapotranspiration, the actual evapotranspiration is equal to precipitation plus the reduction in soil moisture storage, which is found from tables given in the above mentioned publication. In this study the maximum soil moisture holding capacity has been assumed to be 300 millimeters. This value is considered to be an approximate average for most plantation sites in South Africa (J.M. Theron, personal communication, Department of Forest Science, University of Stellenbosch). It is of course important to bear in mind that if the wrong maximum soil moisture holding capacity is assumed this could cause considerable underestimates of the soil moisture deficiencies. Detailed soil surveys should therefore be carried out in order to find actual maximum soil moisture holding capacities if further studies for determining the effect of water stress on growth stresses are to be undertaken.

Temperature data could not be obtained for the Tzaneen area for the period March 1977 to April 1978 because of the temporary closure of the weather station during that period. The mean monthly maximum and minimum temperatures for the two years preceding the period of closure of the weather station were used as estimated temperature values for 1977/78. This procedure is considered acceptable since mean monthly temperatures vary only slightly between years for any given site (Thornthwaite and Mather, 1957).

Table 6.5:- Total monthly rainfall and mean monthly temperature and corresponding soil moisture deficiencies for the Tzaneen area.

March 1977 to April 1978			
Month	Total Rainfall (mm)	Mean temperature (°C)	Soil moisture deficit
March	293	22,2	0
April	41	20,7	2
May	19	18,1	6
June	0	15,3	10
July	0	14,5	11
August	20	17,0	14
September	123	18,7	0
October	28	21,0	19
November	96	22,4	1
December	177	23,0	0
January	698	23,0	0
February	235	23,7	0
March	180	22,2	0
April	25	20,7	4
January 1980 to December 1980			
January	233	23,0	0
February	398	23,3	0
March	120	21,7	0
April	40	20,0	1
May	9	17,8	8
June	0	14,8	9
July	8	14,2	9
August	31	16,4	7
September	68	18,8	0
October	61	20,6	12
November	281	22,8	0
December	144	23,7	0

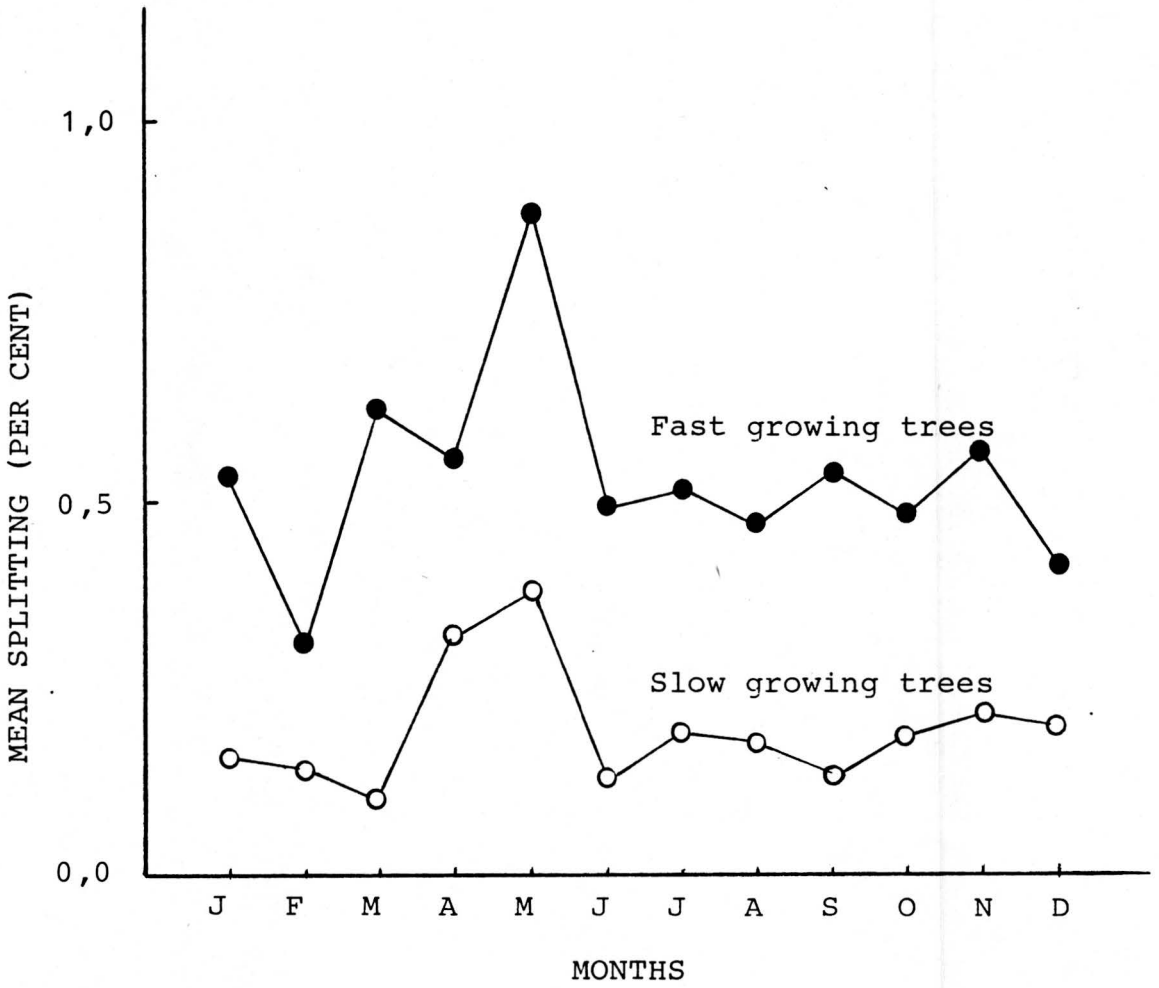

Figure 6.3: Seasonal variation in log end-splitting in trees samples in North-Eastern Transvaal in 1980.

In Figure 6.4 the monthly variation in splitting for the period August 1977 to April 1978 is presented in a graphical form, and is supplemented by a graph showing the monthly variation in soil moisture deficiency for the same period as well as the five-month period preceeding the study period.

Judging from the variations in splitting and soil moisture deficiency there seems to be some merit in the speculations that water stress can have some effect on growth stress levels. A peak period of end-splitting occurred from September to November accompanied by very high soil moisture deficits. With the commencement of the first good summer rains in November the soil moisture deficit dropped to almost zero. This was soon followed by a dramatic drop in stress levels to normal levels in December, giving the impression that actively growing trees respond almost immediately to the restoration of soil moisture. This, however, does not explain the very high splitting values recorded in October following a month of no soil moisture shortage.

Splitting values recorded for August were also fairly close to normal levels despite the fact that this month was preceeded by a long period of water deficiency as a result of the low rainfall during the winter months. It can be speculated that this period of water shortage did not effect the growth stress levels because it occurred during a period of no active tree growth. With the rise in temperatures in September and the resultant initiation of active tree growth, the trees were confronted with a severe shortage of soil moisture, resulting in the generation of higher than normal levels of growth stresses. This condition persisted until November with the start of the first good summer rains.

In 1980 higher than normal splitting values were only recorded for April and May (Figure 6.5), but the increases were less pronounced compared with the increase observed in 1977 for the period September to November. The peak period which occurred in autumn of 1980 is very difficult to explain because no preceeding soil moisture deficiencies occurred. The high splitting values

recorded for that period may possible be attributed to soil moisture deficits which occurred during that late summer period, but this is pure speculation. Unfortunately no splitting assessments were made for the same period in 1977 and consequently it is not known whether a similar splitting pattern occurred.

It is also not possible to explain why no increase in splitting was recorded for the period September to November such as happened in 1977, in spite of the fact that the soil moisture deficit values for the preceeding period showed a very similar pattern to that obtained for 1977 (Figure 6.4).

In this study the existence of a definite seasonal variation in split intensity has been proved once again. It appears, however, that this pattern varies from year to year. Attempts to relate this variation to variation in growth activity and weather conditions yielded contradictory results. There is some indication that weather conditions causing soil moisture shortages during periods of active growth, could give rise to elevated splitting values but this conclusion is based entirely on relationships found in 1977 and experiences of foresters.

6.4.2 Relationship between tree characteristics and level of growth stress

As indicated in section 6.4.1.1 trees from the poor quality site exhibited significantly less splitting than those from the good quality site (Table 6.3 and Figure 6.2). The most obvious inference which could be drawn from this result is that the degree of log end-splitting (level of growth stress) is, among others, a function of the rate of growth.

Considerable between-tree variation occurred in both sites examined and thus provided an excellent situation to study the relationship between level of growth stress in individual trees and the various tree parameters selected to serve as an indirect measure of micro-environment.

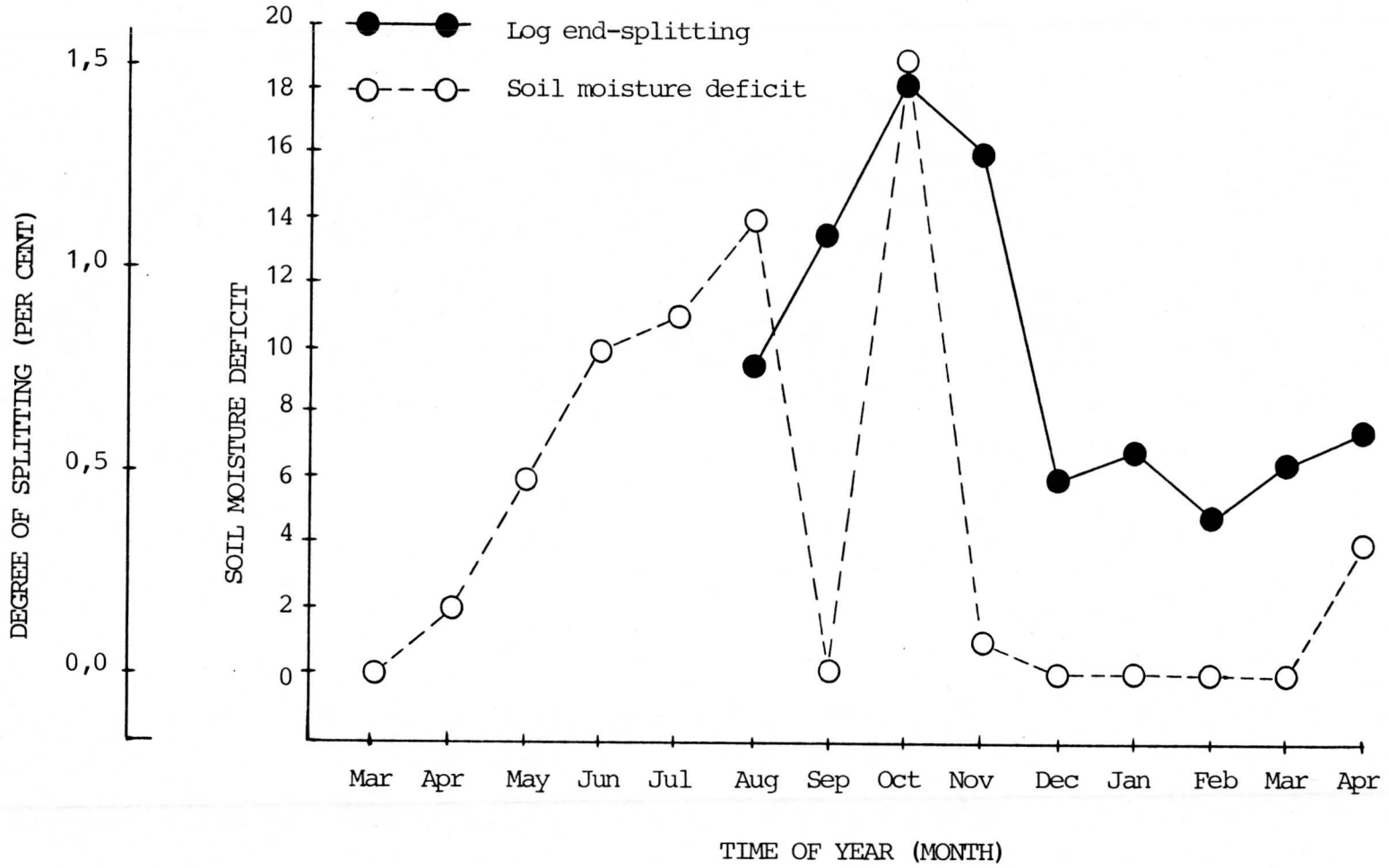

Figure 6.4:- Relationship between log end-splitting and soil moisture deficit for the period March 1977 to April 1978.

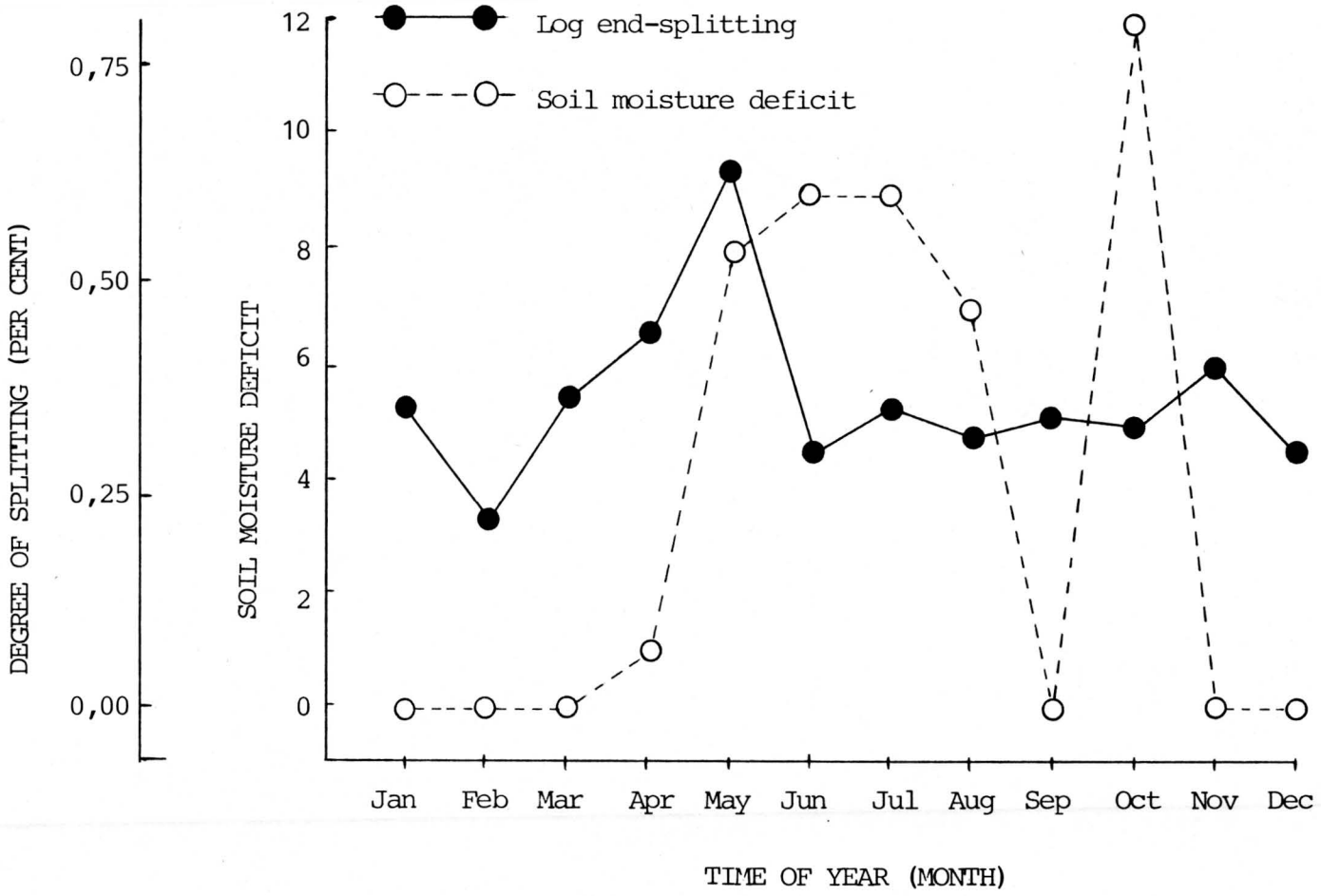

Figure 6.5:- Relationship between log end-splitting and soil moisture deficit for the period January to December 1980 (Tzaneen area).

As a preliminary step, an attempt was made to explain the variation in splitting within stands in terms of the rate of growth as indicated by the diameter at breast height and total tree height. Scatter plots were produced using data obtained from the trees sampled in the good quality site in order to provide some visual evidence of whether any relationship existed between the above mentioned independent variables and mean tree splitting and, if any, what type of relationship it is most likely to be. From Figures 6.6 and 6.7 it is obvious that the relationships are weak because of the fact that the plotted points are widely scattered. The degree of association was examined by computing product-moment correlation coefficients between the two pairs of data.

The correlation between mean tree splitting and diameter at breast height was significant at the 5 per cent level of significance ($r = 0,221$), and that between the former and total tree height was significant at the 1 per cent level of significance ($r = 0,255$). Although this indicates that rate of growth is positively related to the level of growth stress in a plantation grown tree, it explains only a small proportion of the total variation in splitting within stands.

Although total tree height is a function of rate of growth it also involves other factors which could have some effect on stress generation in a tree. One of the major factors is the position of the crown in relation to those in the immediate vicinity. Undoubtedly dominant trees will be more exposed to external forces, such as wind, which could cause such trees to develop higher levels of stresses in their stems acting as a stabilising mechanism to provide the required support to the tree.

In an attempt to establish whether the degree of log end-splitting is related to any of the other tree parameters measured, the degree of association between variables X1 to X17 excluding variables X4, X7, X8 and X9 was examined by computing the product-moment correlation coefficients for all possible

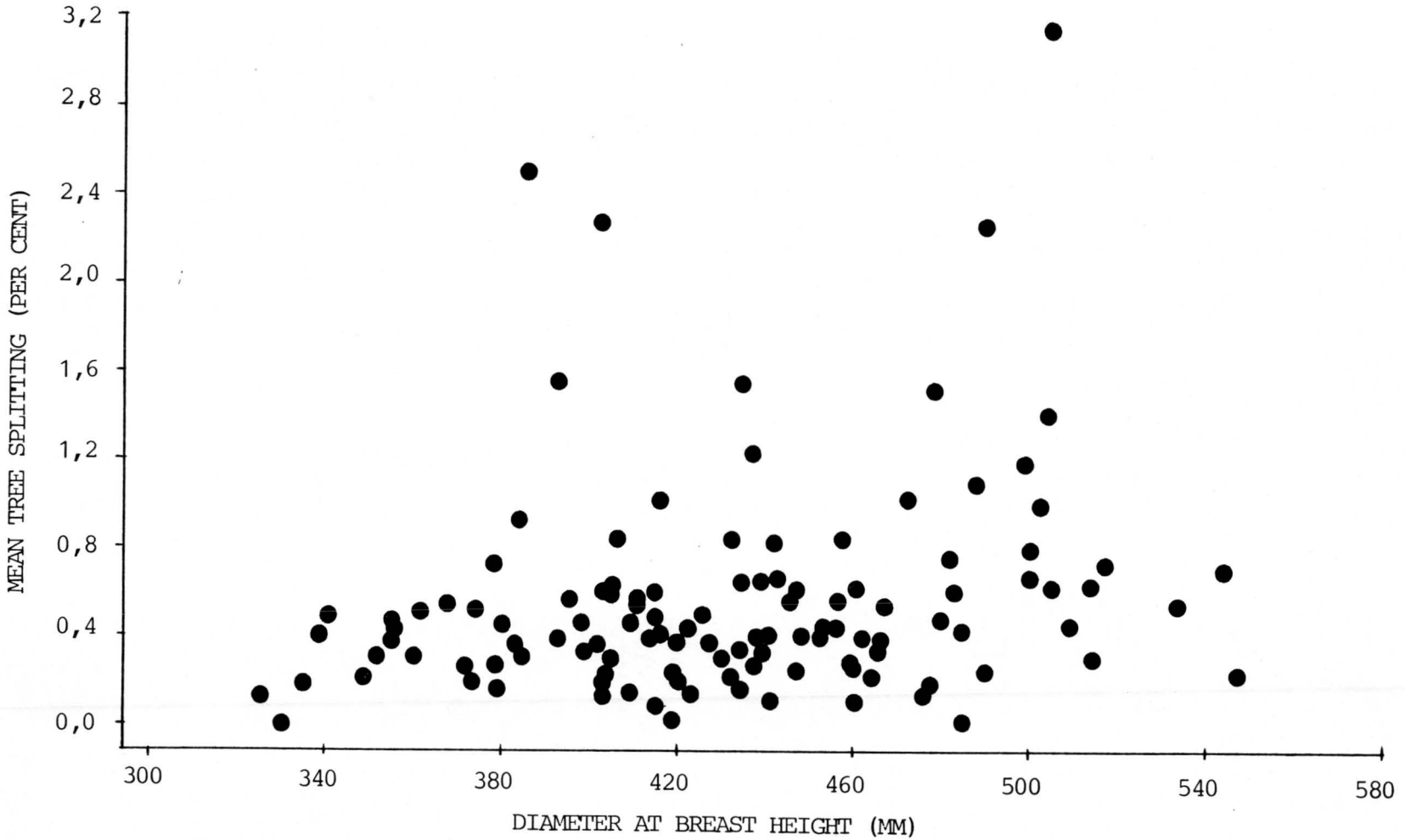

Figure 6.6:- Relationship between mean tree splitting and diameter at breast height.

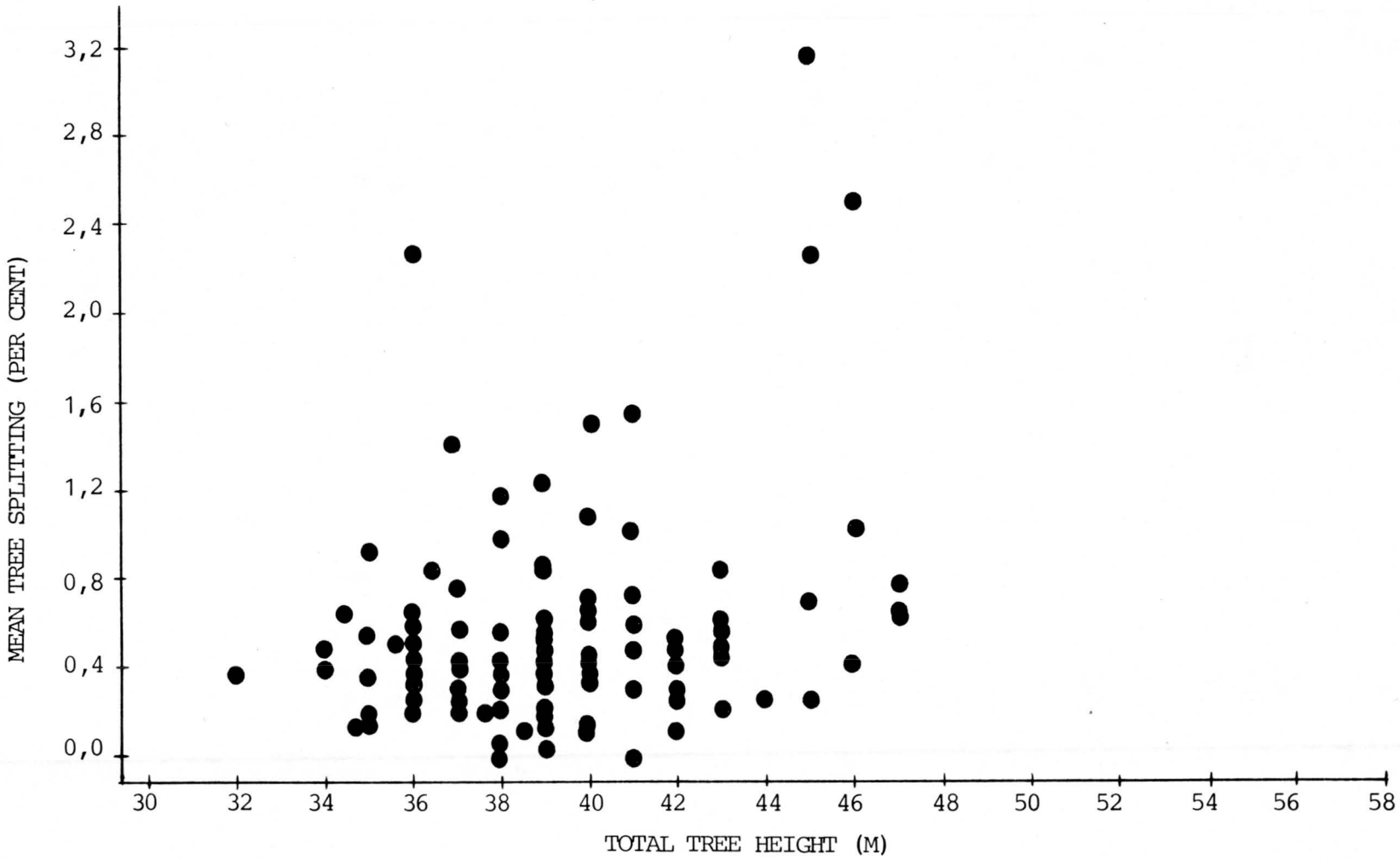

Figure 6.7:- Relationship between mean tree splitting and total tree height.

pairs, using data obtained from the good quality site. The matrix of correlation coefficients between data variables is presented in Table 6.6. The statistical significance of the association between pairs of variables was determined by using tables of values of the correlation for different levels of significance published by Freese (1974). Of the 91 correlation coefficients, 56 are significant at the 5 per cent level of probability or higher. Mean tree splitting correlated well with variables related to rate of growth but showed no statistical significant correlations with any of the other tree parameters measured.

Since the correlation matrix presented in Table 6.6 is of limited value as a means to interpret the variation in the parameters measured, factor analysis based on principal components was subsequently performed. This was done to characterize the meaningful factors describing as much of the total variation in the data as possible, and especially to evaluate the relative importance of the splitting parameter in the total system.

The results of a factor analysis on the data obtained from the trees are given in Table 6.7. From this matrix of unrotated loadings it can be seen that 80,3 per cent of the total variation in the data system of fourteen variables is explained by extracting four factors. The factor cosines (correlations between factors) were relatively close to zero and, as a result, each factor can be considered as describing a distinctly different component of information in the entire set of variables.

The factor loadings given in Table 6.7 are the correlations of a specific factor with the original variables used in the construction of the factors. Since it is difficult to judge the relative importance of each variable in each component, the varimax rotation procedure was utilized in order to achieve more interpretability. The results of the varimax rotation are given in Table 6.8. Factor loadings less than 0,25 have been replaced by zero.

TABLE 6.6: PRODUCT-MOMENT CORRELATIONS COEFFICIENTS BETWEEN ALL POSSIBLE PAIRS OF VARIABLES

Variables	X1	X2	X3	X5	X6	X10	X11	X12	X13	X14	X15	X16	X17	Splitting
X1 (DBH)	1,00													
X2 (TTH)	0,40**	1,00												
X3 (HLB)	-0,13	0,30**	1,00											
X5 (ABL)	0,23*	-0,03	-0,12	1,00										
X6 (ABT)	0,40**	0,10	-0,01	0,77**	1,00									
X10(CP)	0,25**	0,06	-0,88**	0,12	0,05	1,00								
X11 (BNPM)	-0,04	-0,11	0,46**	0,09	0,10	-0,49**	1,00							
X12 (BLSD)	-0,52**	-0,32**	0,42**	0,36**	0,13	-0,49**	0,33**	1,00						
X13 (BTSD)	-0,40**	-0,22*	0,50**	0,29**	0,38**	-0,55**	0,35**	0,88**	1,00					
X14 (SF)	0,76**	-0,29**	-0,34**	0,25**	0,34**	0,20*	0,03	-0,32**	-0,25**	1,00				
X15 (MAI)	0,99**	0,41**	-0,15	0,22*	0,38**	0,27**	-0,05	-0,54**	-0,41**	0,74**	1,00			
X16 (TV)	0,96**	0,63**	-0,02	0,18	0,37**	0,23*	-0,07	-0,52**	-0,39**	0,54**	0,95	1,00		
X17 (TH)	0,39**	-0,14	-0,29**	0,04	0,05	0,19*	-0,08	-0,13	-0,11	0,50**	0,37**	0,31**	1,00	
SPLITTING	0,22*	0,26**	0,11	0,04	0,07	-0,02	-0,03	-0,09	-0,06	0,06	0,22*	0,26**	-0,01	1,00

Statistically significant correlation coefficients (r) are indicated by asterisks, n = 120; * significant at the 5 per cent level; ** significant at the 1 per cent level of probability.

Table 6.7:- Unrotated factor loadings for principal components

Variable	Principal components			
	1	2	3	4
X1 (DBH)	0,921	0,330	0,108	-0,123
X2 (TTH)	0,357	0,147	0,731	0,442
X3 (HLB)	-0,445	0,569	0,621	-0,165
X5 (ABL)	0,161	0,602	-0,520	0,454
X6 (ABT)	0,289	0,703	0,358	0,391
X10 (CP)	0,552	-0,524	-0,378	0,387
X11 (BNPM)	-0,279	0,530	0,112	-0,426
X12 (BLSD)	-0,724	0,492	-0,280	0,059
X13 (BTSD)	-0,634	0,632	-0,211	0,059
X14 (SF)	0,701	0,241	-0,399	-0,448
X15 (MAI)	0,925	0,307	0,113	-0,105
X16 (TV)	0,880	0,324	0,299	0,026
X17 (TM)	0,436	0,032	-0,342	-0,471
SPLITTING	0,214	0,178	0,322	0,174
Variance	4,048	2,800	2,091	1,400
Percentage of total variation explained by each component	35,3	20,0	14,9	10,0
Cummulative percentage explaining total variation	35,3	55,3	70,3	80,3

Table 6.8:- Sorted varimax rotated loadings

Variable	Components			
	1	2	3	4
X14 (SF)	0,932	0,000	0,000	0,000
X1 (DBH)	0,797	0,000	0,563	0,000
X15 (MAI)	0,783	0,000	0,571	0,000
X17 (TM)	0,691	0,000	0,000	0,000
X10 (CP)	0,000	-0,917	0,000	0,000
X3 (HLB)	-0,257	0,874	0,319	0,000
X11 (BNPM)	0,000	0,724	0,000	0,000
X13 (BTSD)	-0,308	0,624	-0,285	0,533
X12 (BLSD)	-0,388	0,549	-0,414	0,473
X2 (TTH)	0,000	0,000	0,924	0,000
X16 (TV)	0,630	0,000	0,741	0,000
X5 (ABL)	0,000	0,000	0,000	0,921
X6 (ABT)	0,000	0,000	0,000	0,875
SPLITTING	0,000	0,000	0,455	0,000
Variance	3,430	2,885	2,709	2,216
Percentage of total variation explained by each component	24,5	20,6	19,4	15,8
Commulative percentage explaining total variation	24,5	45,1	64,5	80,3

To describe 80 per cent of the total variability in *Eucalyptus grandis*, any one of the variables showing a good degree of association with each of the first four factors could be used. Average tree splitting did not appear prominantly until the third factor. In this factor the other variables showing some degree of association with this factor are all variables related to rate of growth. This factor, however, accounts for only 19 per cent of the total variation in tree parameters.

In a final attempt to discriminate between high- and low-stressed trees on the basis of the tree and stem characteristics measured, two extreme stress groups of trees were selected from the 120 trees used in the study. The first group represented trees exhibiting mean tree splitting of less than 0,26 per cent while the second group represented trees with mean tree splitting of more than 0,8 per cent. The major characteristics of the two groups of trees are given in Table 6.9. Apart from variables related to rate of growth, all variables showed no significant difference between these two widely different stress groups.

A discriminant analysis was performed to develop discriminate functions based on the variables listed in Table 6.9 to identify individuals and to assign them to the previously recognized groups of high- and low-stress trees.

The general problem in discrimination is to fit a function of the form:

$$Z = B_0 + B_1X_1 + B_2X_2 + B_3X_3 + \ldots . B_kX_k$$

where: $X_1, X_2, X_3 \ldots\ldots X_k$ are the variables measured, and $B_1, B_2, B_3 \ldots\ldots B_k$ are the corresponding weighting coefficients. The weighting coefficients are assigned such that the ratio of the square of the difference between the means of the groups to the sum of squares within groups are maximized.

Table 6.9:- Mean values of tree and branch characteristics for high- and low-stressed trees. Number of trees per group appear in parentheses.

Variable	Low-stressed trees (28)	High-stressed trees (15)
Mean tree splitting (%)	0,17	1,58
Diameter at breast height (mm)	423,00	453,00
Total tree height (m)	38,27	40,53
Tree volume (m^3)	1,43	1,71
Height to first living branch (m)	17,38	19,27
Crown percentage	55,29	53,87
Branch length (m)	5,86	5,85
Branch thickness (mm)	57,50	59,80
Branch number per metre	0,94	0,94
Branch length/Stem diameter ratio	0,28	0,25
Branch thickness/stem diameter ratio	0,27	0,25
Stability factor	1,10	1,12
Taper per metre	6,67	6,64

The variables used in computing the linear classification functions were chosen in a stepwise manner to obtain information about the importance of the discriminating variables. At each step the variable that adds most to the separation of the groups was entered.

Only "Total tree height" emerged as a possible discriminating variable. The rest of the variables did not contribute significantly to the regression sum of squares.

Classification of an individual was determined by the Mahalonobis D^2 and from the posterior probability for each group. A "Jackknife" procedure was used to reduce the bias in the group classification which involves the testing and classifying of each tree using a discriminant function built upon the rest of the observations. This function unfortunately proved to be ineffective as indicated by the large number of trees that were incorrectly classified (Table 6.10).

Table 6.10. Percentage of trees classified by stress groups using "Total Tree Height" as discriminating variable (Jackknifed classification).

Variable	Low-stressed trees	High-stressed trees
Total Tree Height	78,6	60,0

6.5 Conclusion

In this study an attempt was made to explain the extreme between-tree differences in growth stress levels that are normally observed among plantation grown *Eucalyptus grandis* trees in terms of the tree's immediate environment, using mainly tree and crown characteristics as an indirect measure. An attempt was also made to explain the seasonal variation in stress levels in terms of prevailing soil and climatic conditions.

This study, as .well as others (Malan, 1979a; Hillis, 1978; Okuyama *et al.*, 1981), undoubtedly proved the existence of a seasonal variation in growth stress levels. Although no conclusive evidence could be obtained as regards the relationship between growth stress levels and soil moisture conditions, there seems to be some evidence that actively growing trees tend to develop higher levels of stresses during periods of severe soil moisture shortage. These comments must, however, be considered speculative on present evidence. Clarification of this will require further carefully planned research because there can be no doubt that the mechanisms involved in the tree in elevating stress levels in the stem during certain times of the year, are more complex than has been realized.

Level of growth stress, as revealed by the degree of splitting, varies with height in the tree. In the first 2 to 3 metre the increase is very pronounced but then levels off to an almost constant level. This suggests that butt logs may be more suitable for sawing or peeling.

Fast grown (dominant) trees seem to be more prone to end-splitting and this may explain why splitting in trees from good quality sites tend to be more severe. However, rate of growth accounted only for a small proportion of the considerable variation that occurred among trees growing within the same general environment.

It can logically be assumed that dominant trees within a stand will be more exposed to external mechanical forces. Since these trees are more vigorous, they may have a greater ability to respond to these forces by developing high levels of growth stress.

Although this may be a logical explanation for the correlations found, the general lack of association found between stress and tree parameters proved that mechanical factors are not overriding in effecting level of growth stress in the stems of individual trees of this species, and that factors other than those of environment are involved.

In an attempt to find suitable tree parameters to discriminate between high- and low-stressed trees, only "Total Tree Height" emerged as a possible discriminating variable. However, this variable performed poorly in classifying high- and low-stressed trees effectively. In other words, there seems to be no easily obtainable tree characteristic that can be used to identify low-stressed trees for selection by means of a discriminant function.

Since average tree splitting varies independently of the various tree parameters considered to serve as an indirect measure of environment, it can be concluded that level of stress is principally controlled by the genetic make-up of the tree. It can also be concluded that stem and crown characteristics can be genetically manipulated without any significant detrimental effect on the level of growth stress in tree stems. Furthermore, since no strong relationship was found between growth rate and stress levels, the reduction in stress levels and the increase in volume production could be achieved by simultaneously employing positive selection procedures.

If a significant genetic effect on stress levels can be shown, as well as how stress levels are related to other wood properties, this would be useful for the intelligent planning of an improvement programme aimed at altering the wood properties and general quality of future generations of South African grown *Eucalyptus grandis*.

Results of studies carried out in this respect are reported and discussed in the next two chapters.

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CHAPTER SEVEN

HERITABILITY ESTIMATES FOR GROWTH STRESSES IN *EUCALYPTUS GRANDIS* PROGENY MATERIAL.

7.1 Introduction

In the previous chapter it was shown that only environmental factors influencing the rate of growth and season have a significant effect on the level of growth stress in trees. However, rate of growth only accounted for a small proportion of the extreme differences observed among trees growing within the same general environment. In other words, silvicultural practices aimed at reducing the rate of growth does not appear to be an effective tool in manipulating the level of growth stress.

In view of this, it would be reasonable to assume that a significant part of the observed variation in growth stress is attributable to the inherent potential of individual trees to generate levels of growth stress that differ from neighbouring trees. If this assumption is proved to be correct, considerable gains from tree improvement methods could be achieved in a relatively short period due to the fast growth of *Eucalyptus grandis* and its excellent responsiveness to selective breeding (van Wyk, 1980).

Breeding work on *Eucalyptus grandis* conducted by Andrews (Andrews, 1961; Marsh and Haigh, 1963) and Keet (as reported by Nel, 1962), as well as the selective breeding programme started in 1962 by the Zomerkomst Tree Breeding Station (now known as the J.D.M. Keet Forest Research Station) near Tzaneen, all included low log end-splitting, among other characteristics, as an important selection criterion in their breeding programmes (Nel, 1962; Hodgson, 1967, 1974). Until very recently information on the degree of genetic control over growth stress has been very limited. In spite of this, selection procedures for *Eucalyptus*

grandis employed up to now have all been based on the assumption that the growth stress level in a tree is to some extent controlled by its genetic make-up.

The *Eucalyptus grandis* tree improvement strategy adopted in South Africa has been selective breeding, involving the phenotypic selection of individual trees based on timber and tree properties, the propagation of these phenotypically superior trees in seed orchards for seed production, and the testing of their offspring in replicated trials through which genetic parameters such as heritability, combining ability and genetic correlations are determined.

Because of the slow initial acceptance of plus trees and the delay it imposed on the establishment of progeny tests, only a few small trials had been planted in the period prior to 1975. Two of the most suitable of these tests have been assessed (Malan, 1979a) in order to obtain a heritability estimate for growth stresses. Only one of these trials, consisting of 9 open-pollinated families, showed a statistical significant variation among families. A heritability estimate of 0,20 was obtained, giving a gain prediction of 6,4 per cent in reduced splitting over the population mean (van Wyk, 1980).

The promising outcome of this small study, from a tree improvement point of view, not only confirmed the correctness of the assumption made in the past as regards the heritability of growth stresses, but also stressed the need to obtain a more accurate estimate of the genetic contribution to the variability in this phenomenon. A more exact heritability estimate will enable tree breeders to predict the expected genetic gain in reduced splitting over the population mean more accurately and, at the same time, enable them to plan future tree improvement programmes more efficiently.

7.2 Materials and methods

The first diallel progeny test planted in South Africa was established in January 1975 and consisted of 72 controlled pollinated families. This trial was supplemented by an open-

pollinated progeny test of 99 families established in the same planting season. Both trials were situated in the North-Eastern Transvaal on research sites of the J.D.M. Keet Forest Research Station.

At the age of about 6 years the trees of both trials were evaluated as regards various tree characteristics and wood properties, including log splitting. Because of the small size of the average log prepared from the trees sampled, the traditional method of end-split assessment could not be considered because of its inability to measure small amounts of end-splitting with the required precision. A point scoring system specifically developed to overcome this shortcoming was therefore applied (Conradie, 1980; Appendix One).

It was invisaged that these properly designed trials, both representing the beginning of comprehensive progeny testing of *Eucalyptus grandis* in South Africa, would provide sufficient data to determine the degree of genetic control of growth stress.

The determination of the magnitude of the genetic control and environmental components of the total phenotypic variability in growth stress levels, is based on the partitioning of the total phenotypic variance (σ_p^2) into variance due to gene effects (σ_g^2), variance due to environmental effects (σ_e^2), and variance due to the interaction between the two (σ_{eg}^2):

$$\sigma_p^2 = \sigma_g^2 + \sigma_e^2 + \sigma_{eg}^2$$

The genotype variance (σ_g^2) can be partitioned into the following components:

σ_a^2 = additive genetic component of variance.
σ_d^2 = dominance component of variance.
σ_i^2 = epistatic or interaction component of variance.

Thus,

$$\sigma_p^2 = (\sigma_a^2 + \sigma_d^2 + \sigma_i^2) + \sigma_e^2 + \sigma_{eg}^2$$

Only the additive genetic component of variance (σ_a^2) has the quality of predictability necessary in formulating breeding plans. When expressed as a proportion of the total phenotypic variance, it is known as the narrow-sense heritability:

$$h^2 \text{ (narrow-sense)} = \frac{\text{Additive genetic variance } (\sigma_a^2)}{\text{Total phenotypic variance } (\sigma_p^2)}$$

The dominance variance (σ_d^2) and the epistatic variance (σ_i^2) measure the intra-allelic and the inter-allelic interaction respectively. When both additive and non-additive components of variance is expressed as a proportion of the total phenotypic variance, it is referred to as the broad-sense heritability:

$$h^2 \text{ (broad-sense)} = \frac{\text{Total genetic variance } (\sigma_g^2)}{\text{Total phenotypic variance } (\sigma_p^2)}$$

7.2.1 The open-pollinated progeny trial

During the mid-seventies an acute shortage of improved seed was experienced, mainly as a result of the slow rate of accepting plus trees caused by the timber quality evaluation techniques followed by the South African Forestry Research Institute at that time (see: Banks and van Vuuren, 1976 and de Villiers, 1973).

Although the existing clonal seed orchards at that time managed to produce sufficient seed for the establishment of sawlog plantations, an overall shortage of seed was experienced due to a heavy demand for the establishment of plantations for the production of a wide variety of various other raw materials. The slow rate of accepting new genotypes also hampered the objective to obtain a wide genetic base.

In order to solve these problems a series of open-pollinated trials, each consisting of 99 open-pollinated families and comprising an area of 1,85 hectares, were established.

The first plot in the series was sampled at the age of 5½ years to study the variation in end-splitting among families. This test included open-pollinated progenies of trees selected on outstanding phenotypic characteristics, a commercial control from Westfalia Estate plantations (Letaba district), a seedlot from Argentina, and six seedlots from different Zimbabwian clones. Also included were a number of open-pollinated progenies originating from parent trees which were rejected on poor sawn results, but which nevertheless were retained in the breeding programme due to their otherwise excellent tree characteristics.

Nine replications of four-tree experimental plots (2,1 metre square) were established in a randomized complete block design giving a total of 36 trees per family treatment.

Square plots were adopted to ensure a more scattered pattern of the remaining trees of a 75 per cent thinning of all families throughout the test planting area. This layout also ensured random pollination and sufficient spatial difference among members of the same family, i.e. among half-sibs.

At the age of approximately 2 years, stem straightness and volume production were assessed, followed by 50 per cent thinning (two trees per experimental plot). Eleven months later total tree height and diameter breast height were measured and stem form was

again assessed. Based on the results of the analyses carried out on this data, all families were screened and the least 39 promising families removed from the experiment. The remaining trees were immediately reduced to only one tree per experimental plot.

At the age of about 6 years all the trees were felled and the diameter at breast height, total tree height, wet and dry capsule mass, wet and dry seed mass and the amount of log end-splitting determined. Thirteen plots contained no trees giving a total sample size of 527 trees.

The degree of splitting was assessed at ground level, at 2,4 metre height and at midpoint of the remaining stem. Score values for splitting were assigned following the procedure described by Conradie (1980) and adjusted for log end diameter (Appendix Two).

7.2.2. The controlled-pollinated trial

In order to estimate both additive and non-additive components of inheritance, sample material was collected from the first *Eucalyptus grandis* diallel progeny test established in South Africa.

The trial consisted of seventy-one controlled-pollinated progenies (families) and one control. The progenies resulted from pollinations made according to the techniques described in detail by Hodgson (1967, 1974, 1975). A partial diallel mating design (Table 7.3) was used because results have shown proved that this mating design provides very useful information in the testing of trees selected for saw timber production (Van Wyk, 1980).

Twenty parents were involved in the crosses. Seventeen served as both males and females, two served only as males, and one served only as a female. The parents were previously selected for vigor, stem form, and branch and crown characteristics. Thus,

the design was incomplete and unbalanced with 71 degrees of freedom for crosses (families), 17 degrees of freedom for female parents, 18 degrees of freedom for male parents and 36 degrees of freedom for the male x female interaction.

An 8 x 9 rectangular pattern design with three replications was used in establishing the trial following the plans recommended by Cochran and Cox (1957). In each replication every two-parent mating was represented by a row of ten trees. A planting espacement of 2,7 by 2,7 metres was used. The trial covered an area of 1,88 hectares and was bordered by a two-row surround consisting of trees grown from excess seedlings.

At the age of 6 months all tree heights were recorded. Three years later tree heights, diameter at breast height, branch characteristics and stem form were recorded. This was followed by a 40 per cent thinning.

At the age of about 5½ years a random sample of two trees per experimental plot was taken. The basal part of each tree sampled was cut into a 4,8 metre log. The degree of end-splitting was assessed on both ends using the point scoring system previosuly mentioned and described in Appendix One. The four splitting values obtained from the two trees from each experimental plot were adjusted according to stem diameter, averaged and used in the statistical analysis. In eight plots only one tree was available for sampling thus giving only two split values per plot.

7.3. Results of statistical analysis

7.3.1. The open-pollinated trial

The inclusion of progenies of both high- and low-stressed trees in this trial, provided an excellent opportunity to evaluate the effect of selective breeding on this trait.

The performance, as regards to splitting, for the offspring of all South African selections tested by the trial, is presented in Table 7.1. This was done by comparing the amount of splitting in progenies of accepted and rejected parent trees. To test the statistical significance of the differences between the means of the two groups of trees, a simple t-test was performed. The mean degree of splitting in the progenies of high-stressed trees was significantly higher compared to the progenies of low-stressed trees.

From this comparative study there is clear evidence that the selection of low-stressed parents reduce the mean degree of end-splitting (growth stress) over that of the mean in the previous generation.

In order to obtain information on the relative contribution which genes make to the variation in growth stress, an analysis of variance was performed to test the significance of the family variation in log end-splitting. Since the frequency distribution was found to be skewed to the right, a natural logarithmic transformation was applied to make the data more symmetrical in order to satisfy the assumptions of the analysis (Sokal and Rohlf, 1969). The results of the analysis is given in Table 7.2)

Since the analysis indicated a highly significant family variation, components of variance were separated and heritability determined in order to obtain an estimate of the degree of genetic control over growth stresses.

In this material which was propagated by sexual means, non-additive genetic variance caused by dominance and epistasis cannot be detected. The narrow-sense heritability was therefore calculated. This is defined as the ratio of additive genetic variance to total phenotypic variance. Assuming the relationship between families to be half-sib (families having one common parent), the estimate of heritability is given by:

Table 7.1:- Performance of the progenies of high and low split *Eucalyptus grandis* trees selected for tree breeding.

	PARENTS		PROGENY
	Mean log end-splitting[1] (per cent)	Mean sawn yield index[2]	mean split score[1]
Accepted trees	0,9	7,5	3,8
Rejected trees	1,6	-9,3	5,4
t-test	**	**	**

1) See Appendix One.
2) See Appendix Two.
** Significant at 1 per cent level

Table 7.2:- Analysis of variance of splitting in open-pollinated progenies of .

Source of variation	Degrees of freedom	Mean square	F-ratio	Expectation mean square
Replications	8	0,07372	1,16ns	$\sigma_e^2 + 6\sigma_r^2$
Families	59	0,15712	2,48**	$\sigma_e^2 + 9\sigma_f^2$
Residual	459	0,06346		σ_e^2
Total	526			

ns = Non-significant
** = Significant at 1 per cent level of probability.
σ_r^2 = Variance due to diiference among replications.
σ_f^2 = Variance due to difference among families.
σ_e^2 = Variance which cannot be explained.
σ_r^2 = $(MS_r - \sigma_e^2)/60$ = 0,000171
σ_f^2 = $(MS_f - \sigma_e^2)/9$ = 0,010407
σ_e^2 = 0,063460

$$h^2 = \frac{4\sigma_f^2}{\sigma_e^2 + \sigma_r^2 + \sigma_f^2}$$

where: $4\sigma_f^2$ = an estimate of the additive genetic variance.

$\sigma_e^2 + \sigma_f^2 + \sigma_r^2$ = an estimate of the phenotypic variance.

The heritability estimate was as follows:

$$h^2 = \frac{4 \times 0{,}010407}{0{,}06346 + 0{,}010407 + 0{,}000171}$$

$$= 0{,}56$$

The standard error of the heritability estimate was calculated using the formula for the standard error of an intraclass correlation coefficient:

$$\text{S.E. of } h^2 \text{ (narrow-sense)} = \frac{(1-t)(1+Rt)}{R(F-1)/2}$$

$$= 0{,}16$$

7.3.2. The controlled-pollinated trial

In Table 7.3 the summarized data from the diallel progeny test are arranged by parental lines and columns.

An analysis of variance was performed on the plot means (Table 7.4). The expectation mean squares were calculated in order to obtain an estimate for both narrow-sense and broad-sense

heritability. In the partitioning of the variance the effective number of female parents was computed as the harmonic mean of the number of females crossed with each male parent (Bingham *et al.*, 1960). The same method was used to determine the effective number of male parents.

There are many versions of heritability formulae depending on the type of mating design used, or on the genetic history of the organism being investigated (Bingham *et al.*, 1960). Since this experiment consisted of sexual progenies which resulted from crosses between parents whose genetic constitution were unknown, the following formulae, considered to be the most appropriate for this type of experiment, were been used for estimating heritability (Bingham *et al.*, 1960):

$$h^2(\text{narrow-sense}) = \frac{\sigma_f^2 + \sigma_m^2}{\sigma_e^2 + \sigma_f^2 + \sigma_m^2 + \sigma_{fm}^2}$$

$$h^2(\text{broad-sense}) = \frac{\sigma_f^2 + \sigma_m^2 + \sigma_{fm}^2}{\sigma_e^2 + \sigma_f^2 + \sigma_m^2 + \sigma_{fm}^2}$$

Respective heritability estimates were as follows:

$$h^2(\text{narrow-sense}) = \frac{1,0207}{1,8306} = 0,56$$

$$h^2(\text{broad-sense}) = \frac{1,0502}{1,8306} = 0,57$$

Table 7.3:- Average log splitting score of 71 control-polinated progenies (plus 1 control) used in the heritability analysis (Tabulated values are averages of 6 trees).

FEMALE PARENTS	MALE PARENTS																		AVERAGE
	4	6	10	15	17	19	22	35	36	37	38	39	44	45	58	60	64	66	101	
4		2,5		4,4								2,5			4,6					3,5
6	2,0					1,6														I,8
10		1,2							1,3						1,7	1,4	1,0	1,8	2,9	1,6
15		3,1										3,8	,8			3,0		2,3		2,6
17													1,7		1,8		1,3			1,6
22										4,1					2,3	1,5		2,3		2,6
35	2,6			2,7						2,8										2,7
36		1,6				2,1				2,9	2,0	1,5								2,0
37	4,2												2,1							3,1
38																			2,7	2.7
44	2,5	1,0		1,2			1,2	1,2		1,7						1,4				1,5
45				3,5			2,2						1,7		2,7		1,0		2,6	2,3
50	1,6		1,5			1,8	2,9						1,5						1,3	1,8
58	3,6				2,0							3,3								3,0
60						1,4														1,4
64		1,8										1,6			2,7	2,9				2,2
66						2,4						1,9								2,1
101	3,5				2,3	3,3				2,9	5,0			3,2						3,4
AVERAGE	2,9	1,9	1,5	3,0	2,1	2,1	2,1	1,2	1,3	2,9	3,5	2,4	1,5	3,2	2,6	2,0	1,1	2,1	2,4	

Control 1,4

Table 7.4:- Analysis of variance of end-splitting in controlled-pollinated matings.

Source of variation	Degrees of freedom	Mean square	F-ratio	Expectation mean square
(Family)	(71)	(2,6853)	(3,44**)	
Female	17	5,2882	6,78**	$\sigma_e^2+3\sigma_{fm}^2+3X2,5552^{(1)}\sigma_f^2$
Male	18	3,8602	4,95**	$\sigma_e^2+3\sigma_{fm}^2+3X2,2448^{(2)}\sigma_m^2$
F X M	36	0,8687	1,11ns	$\sigma_e^2+3\sigma_{fm}^2$
Replication	2	1,4336	1,84ns	
Residual	142	0,7804		σ_e^2
Total	215			

** Significant at the 1 per cent level
ns Non-significant
(1) Harmonic mean of the number of males crossed with each female.
(2) Harmonic mean of the number of females crossed with each male.

Variance components: $\sigma_e^2 = 0,7804$
$\sigma_f^2 = 0,5765$
$\sigma_m^2 = 0,4442$
$\sigma_{fm}^2 = 0,0294$

7.4. Discussion

Growth stresses in *Eucalyptus grandis* appear to be sufficiently heritable to enable its genetic manipulation. This, coupled with the considerable phenotypic variation characterizing this species, its fast growth, and its excellent response to selective breeding, would result in a considerable reduction in growth stress levels in a tree breeding programme. The genetic gain, would, of course, also depend on the selection intensity applied.

The results of the open-pollinated trial provided clear evidence that end-splitting is heritable, but the actual estimate of heritability optained should be regarded as of dubious value because of the culling of families prior to sampling for this study. In other words, measurements were made on a selected sample.

The results of the controlled pollinated matings are difficult to interpret genetically because of the inbalance of the mating design. One has no confidence in the unbiassedness of the heritability estimates, as would be in the case of a balanced design. However, the results again provided clear evidence for genetic variation.

The inclusion of low log end-splitting as one of the important selection criteria in the genetic improvement programme for South African Eucalypts, has been substantiated by these studies. The opportunity now exists for the more efficient planning of future selection of low-stressed trees for propagation and eventual use in afforestation. This seems to constitute a promising long-term solution to the utilization problems related to high levels of growth stress in trees.

In view of the success obtained with the rooting of cuttings of *Eucalyptus grandis* (van Wyk, 1980), vegetative propagation in conjunction with tree selection, will make it possible to obtain

a greater genetic gain than by sexual propagation. The relatively high broad-sense heritability obtained is thus of considerable importance.

It must be emphasized that, although genetic variation has been detected for end-splitting and therefore response to selective breeding can be expected, the response is not predictable with any accuracy from the estimates of heritability obtained.

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CHAPTER EIGHT

ASSOCIATION BETWEEN WOOD CHARACTERISTICS AND GROWTH STRESS INTENSITY

8.1 Introduction

Results obtained in this study so far indicated that the variation in level of growth stress in *Eucalyptus grandis* is largely independent of environmental factors and confirms similar results obtained for other Eucalypt species (Nicholson, 1973a). Although this, as well as other studies indicated a positive relationship between growth stress intensity and rate of growth (Waugh, 1974; Hillis, 1978), the present study showed that rate of growth accounts for only a relatively small proportion of the extreme differences normally observed among trees growing within the same general environment.

In view of this, it seems unlikely that silvicultural practices aimed at manipulating rate of growth or any other tree characteristic, would serve as an effective tool to reduce level of growth stress in plantation grown Eucalypts. However, good results might be obtained on species such as Poplar which are more demanding on site and are probably much more sensitive to the manipulation of the environment through silvicultural techniques (Waugh, 1972).

Various attempts and techniques to reduce existing stresses in trees and logs to more acceptable levels, or to reduce the effect of high stress prior to or during conversion, have also met with limited success (Barnacle and Gottstein, 1968; Dinwoodie, 1966; Giordano and Currò, 1972 and 1973; Malan, 1979b; Conradie, 1980; Nicholson, 1973a; Priest, 1981 and 1984; Iman *et al.*, 1972; Skolmen, 1967; Barnacle, 1970; Giordano *et al.*, 1969; Waugh, 1974 and 1977; and many others). Although some of these techniques might help to maximise conversion efficiency, it is still very far from a real solution.

Since this study has undoubtedly proved the existence of a genetic variation in growth stress intensity, response to selection can be expected. Hence, the selection of low-stressed trees seems to constitute the most effective and most promising long-term means of growth stress reduction in trees.

However, the use of growth stress as an important selection criterion would be compromised if important production variables such as wood density, fibre length, ect. are adversely affected by the selection. On the other hand good relationships could provide variables which could be used for the fast and easy identification of low-stressed trees in a tree breeding selection programme.

In leaning Eucalypt trees there is a gradation of growth stress around the stem with maximum values in the vicinity of the opposite side of the lean (Malan, 1979a; Nicholson *et al.*, 1972, 1973b, 1975). In *Eucalyptus regnans* it has been shown that this stress gradation is strongly associated with the cell structure which in turn determines various physical properties such as volumetric shrinkage, basic density, percentage Klason lignin and modulus of elasticity (Nicholson *et al.*, 1973b). Nicholson *et al.* (1972) concluded that much of the variation in wood properties generally observed within trees, might well be explained by these relationships. Furthermore, these relationships might also explain the variation in wood properties between trees since level of growth stress has been found to vary considerably among trees.

If such relationships are confirmed for *Eucalyptus grandis*, this would help to explain the considerable variation in wood properties that exists both within and between tree stems. It would also be of considerable importance for the planning of a tree breeding programme aimed at altering level of growth stress and wood properties in future generations of this species.

The purpose of this study was twofold: first, to conduct a preliminary investigation of the relationship between level of

peripheral stress and the properties of the wood within trees, i.e. within the same basic genetic make-up; and second, to establish whether the observed among-tree variation in wood properties could be related to between-tree differences in growth stress levels. With the latter study it was intended to provide useful evidence as to which important production variables will be affected as a result of the genetic manipulation of the stress level in trees. Attempts were also made to develop discriminant functions based on easily measurable variables which could be used to identify low-stressed individuals for the selection in breeding programmes. As there is an urgent need for early evaluation of level of growth stresses in progeny and provenance trials, study samples prepared from the juvenile zone of the stem were included in the study.

8.2 Experimental material

8.2.1 Within-tree variation study

Study trees were selected from a 20-year-old *Eucalyptus grandis* stand in the North-Eastern Transvaal near Tzaneen to examine the within-tree relationship between the longitudinal peripheral stress and various wood properties. The selection method used was one of selecting two healthy trees showing a strong crown offset from the stump. Previous studies have indicated that the variation in peripheral stress is closely related to the needs of the tree for mechanical support (Nicholson, 1973b). The selection of leaning trees thus provided the opportunity to study the properties of wood obtained from positions of varying growth stress intensities.

At breast height (approximately 1,3m from ground level) a strip of bark (about 300mm wide) was removed and eight equally spaced positions were marked off on the same circumferential line. Longitudinal tensile growth strain was measured at these positions following a technique developed by Nicholson (1971a) and modified by Malan (1979a). This method principally comprises the

measurement of the amount of longitudinal growth strain that occurs as a result of the release of stress on the surface of the tree stem.

The procedure for measuring was as follows: the wet slimy tissues underlying the bark were scraped clear, and allowed to dry for a few minutes. Following this, gauge points were fixed onto the prepared surface at a gauge length of 50mm using a setting out bar. Bostik cyano-acrylate adhesive (Type CF) was used which provided a secure bond between the slightly damp wood surface and the gauge points (provided the surface was flat enough to allow uniform contact with the flat under surface of the gauge points). This special adhesive was selected for its very short setting time. Although it is sensitive to moisture it allows ample working time to complete the entire procedure. Longitudinal strain relief was affectuated by drilling holes (38mm in diameter and 25mm deep) on either side of the area prepared for strain measurement (Figure 8.1). To avoid wind induced peripheral strains, all readings were carried out on a calm day.

Strain relief was measured using a Demec mechanical strain gauge which gives readings with an accuracy of approximately 3×10^{6}. The instrument consists of an Invar beam with two conical locating points, one in a fixed position at one end, and the other, pivoting on a special knife edge. (For more details on the design and use of this mechanical strain gauge, see Morice and Base, 1953, and Base, 1955.) Stainless steel locating discs (gauge points) were used.

Within the elastic limit of wood the peripheral growth strain measured is closely associated with the stress requirements for support at the position measured (Nicholson, *et al.*, 1972, 1975). Mean strain values could, therefore, be directly compared and conclusions drawn as regards the association between the level of growth stress and the various wood properties considered.

Following strain measurement, the trees were felled and a stem

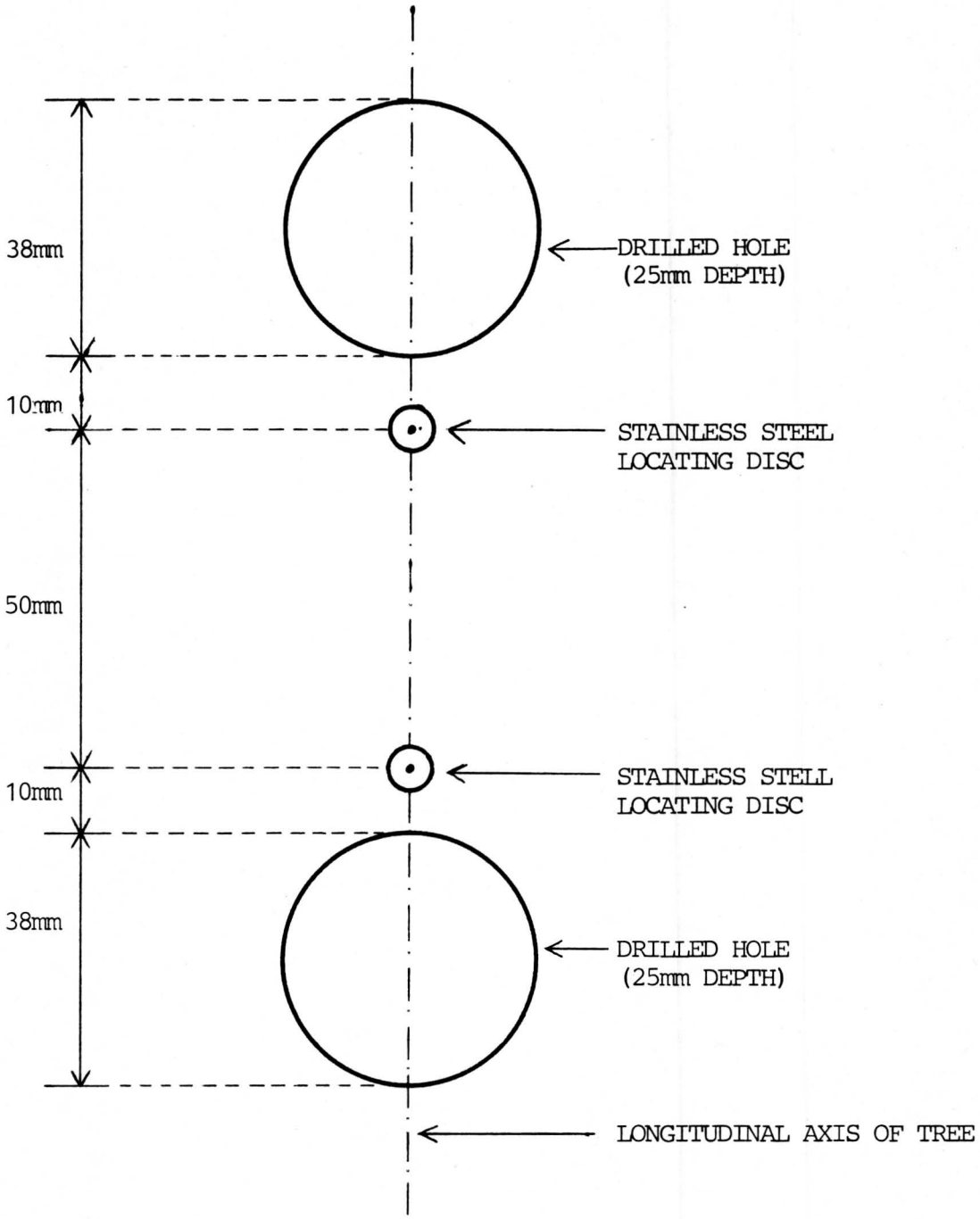


Figure 8.1:- Method applied to relieve longitudinal growth stress to allow surface strain measurement.

section, 500mm in length, centered on the circumferential line where the strain readings were taken, was removed from each tree. End-matching each strain measuring position, longitudinal strips (25mm by 25mm square) were machined and further cross-cut to yield material to determine the wood properties listed in Table 8.1.

8.2.2 Between-tree variation study.

In April 1983, a total number of 30 *Eucalyptus grandis* trees were randomly selected in compartment B26 of Wilgeboom State Forest. It is situated in the Eastern Transvaal Lowveld about 50 kilometers from Sabie. To reduce the incidence of reaction wood, only near vertical trees were selected.

This stand was established in 1955 at a stocking of 1 000 trees per hectare. In 1959 it was thinned to 800 trees per hectare and again in 1963 to 500 trees per hectare. In 1968 it was finally thinned to the present stocking of 311 trees per hectare. In 1972 a mean annual increment of 50 cubic metre per hectare was recorded. The mean tree height and diameter at breast height were 39,5m and 400mm respectively.

Before felling, the overbark breast height diameter for each tree was recorded. After felling, the basal part for each tree was divided into three 3,7m logs starting at breast height. Discs, 75mm thick, were removed at 1,3m and 5,1m heights, and immediately sealed in plastic bags.

All 90 logs were left unbarked in the plantation for 72 hours. At the end of this period the log ends were photographed and the following data was accurately recorded:

(i) Number of radial splits not extending to the periphery of the cross-section (Type A splits).
(ii) Score value of Type A splits.

(iii) Number of splits that extended to the peripery of the cross-section (Type B splits).
(iv) Score value of Type B splits.
(v) Maximum and minimum diameter of heartwood zone (mm).
(vi) Maximum and minimum radius (mm).

All measurements and score values were carried out by the candidate to try and ensure uniformity.

The following variables were derived for each log end:

(i) Eccentricity = Maximum radius/Minimum radius.
(ii) Ovality = Maximum diameter/Minimum diameter.
(iii) Heartwood proportion = Mean heartwood diameter/Mean diameter of cross-section.
(iv) Taper = (diameter at 1,3m - diameter at 12,55m*) /11,25**
(v) Split Score (adjusted) = (Total Score*** X 100)/Diameter of cross-section in millimeters.

* Height above ground level at top of third log (m).
** Bole length between butt of first log and top of third log (m).
*** Type A and Type B splits combined.

Table 8.1:- List of measured and derived variables assessed to study growth strain/wood property relationships within and between trees.

Variable description	Unit
Basic density	$g.cm^{-3}$
Radial shrinkage to 10 per cent e.m.c.	per cent
Tangential shrinkage to 10 per cent e.m.c.	per cent
Longitidinal shrinkage to oven-dry	per cent
Volumetric shrinkage to oven-dry	per cent
Fibre length	millimeters
Double-wall thickness of fibres	micrometers
Wall thickness of fibres	micrometers
Lumen diameter of fibres	micrometers
Fibre diameter	micrometers
Fractional wall volume of fibres	per cent
Fractional void volume of fibres	per cent
Fibre content per unit volume	per cent
Vessel diameter (tangential)	micrometers
Number of vessels per square millimeter	-
Vessel content per unit volume	per cent
Ray width	micrometer
Ray frequency	-
Ray content per unit volume	per cent
Runkel ratio	-
Fibre flexibility coefficient	-
Felting coefficient	-
Fibre density	-

8.3 Laboratory methods.

8.3.1 Determination of basic wood density.

Due to its heterogeneous nature and the fact that it changes in volume with changes in moisture content, wood density can be expressed in several ways (see: Davidson, 1972).

For this particular study, basic density was determined as the ratio of the oven-dry (moisture-free) mass of the sample to its saturated (water-logged) volume.

Although basic density does not represent the density of wood in any condition ever found in practice, it is of value in scientific investigations as this method of expressing wood density overcomes the complications caused by varying shrinkage and collapse.

All specimens prepared for density determination were sanded to a smooth surface to remove loose surface fibres. This minimized the possibility of air bubbles clinging to the surface of the sample during water-immersion to ensure that the water could adhere closely.

Basic density was obtained gravimetrically through the following formula:

$$\text{Basic density} = \frac{M_{od}}{M_f - M_{fs}}$$

where: M_{od} = oven-dry mass of sample in air (g).
M_f = mass of beaker filled with distilled water (g).
M_{fs} = mass of beaker filled with distilled water while saturated sample was immersed in water (g).

Since the samples were kept in the green condition they remained swollen to maximum volume. However, complete saturation was thought desirable to ensure that no water absorption took place during immersion when the sample volume was determined. For this reason samples were placed in an autoclave and a vacuum of about -90kPa was applied for eight hours. This was followed by a three hour period during which a pressure of 600kPa was applied. The process was repeated twice since it was hard to judge when the saturated condition was reached. At the end of three vacuum/pressure cycles, the samples were regarded as completely water-logged.

The samples were finally left submerged in water under normal atmospheric pressure for two days to allow the entire cell structure of each sample to regain normal pressure and shape (Manseau, 1979; Vermaas, Department of Wood Science, University of Stellenbosch, personal communication). The saturated volume was determined by completely submerging the sample in a glass container filled with distilled water placed on a top loading balance. The change in mass as a result of water immersion gave an exact measure of the volume of the sample (Olesen, 1971).

A pin (approximately 1mm in diameter) was inserted into the sample parallel to the grain to a constant depth, sufficiently deep to hold the sample. Great care was taken to ensure that each sample was completely submerged during measurement and that it did not touch the inner walls of the beaker.

In the case of samples of varying sizes a constant immersion depth for the pin itself could not be maintained. By keeping the water level in the beaker constant and by adjusting the height of the tip of the empty pin while in a resting position so that it just touched the water surface, the displacement caused by the pin when the wood sample was submerged was kept to a constant percentage of the sample volume. In view of the relatively large

size of most of the samples, and the fact that the raising of the water level in the beaker was kept to a minimum by using the largest diameter beaker which would fit on the balance pan, this error could be reduced to a negligible level.

The oven-dry mass of the samples was determined after drying the specimens for 48 hours in an oven at 103°C to constant mass, and cooling in a desiccator to room temperature to prevent moisture absorption from the atmosphere.

8.3.2 Volumetric shrinkage

Clear test pieces were prepared to determine volumetric shrinkage from green to oven dry. These samples measured approximately 25mm x 25mm x 64mm (the 64mm being in a direction parallel to the grain) and were cut from green wood. To avoid water absorption during the brief immersion needed to determine green volume, the green specimens were submerged in water and then subjected to vacuum and then to pressure as described above. After this treatment the samples were left submerged in water for a period of two days at normal atmospheric pressure to allow the samples to regain their normal green volume.

The volume of water-logged samples were determined to the nearest 0,01cm^3 by immersion in distilled water at 20°C. Following this, the samples were allowed to dry. To restrict the rate of drying the samples were placed in a conditioning chamber and slowly dried to an equilibrium moisture content of about 12 per cent. At this point the samples were oven-dried at 103°C to constant mass and were immediately placed in a air-tight desiccator and allowed to cool to room temperature. Thereafter the samples were weighed to determine the oven-dry mass and then immediately dipped into hot paraffin wax to avoid re-absorption of moisture during volume determination. The volumes of the oven-dry specimens were then determined as described above.

Volumetric shrinkage was calculated as follows:

$$S_v = \frac{V_g - V_o}{V_g} \times 100$$

where: V_g = green volume
V_o = oven-dry volume
S_v = volumetric shrinkage from green to oven-dry (per cent).

8.3.3 Radial, tangential and longitudinal shrinkage

Green samples measuring 25mm x 25mm x 104mm were used to determine radial and tangential shrinkage from green to 10 per cent moisture and longitudinal shrinkage from green to 0 per cent moisture content. The use of a single specimen to determine the above mentioned three types of shrinkage is in accordance with the findings of Kelsey and Kingston (1957).

A dial gauge, capable of measuring to an accuracy of 0,001mm, was used to determine the radial, tangential and longitudinal dimensions of the specimens. The dial gauge was fitted onto an aluminium sample holder (xylometer) which ensured that both readings were taken exactly on the same spot.

After complete water saturation the radial, tangential and longitudinal dimensions of the samples were recorded. The samples were then slowly dried in a conditioning chamber. At a 10 per cent equilibrium moisture content the radial and tangential dimensions of the samples were again recorded. Finally the samples were oven-dried to determine longitudinal shrinkage from green to zero per cent moisture content.

Radial, tangential and longitudinal shrinkages were calculated as follows:

(a) Radial shrinkage

$$S_r = \frac{R_g - R_a}{T_g} \times 100$$

where: R_g = radial dimension green.
R_a = radial dimension at 10 per cent moisture content.
S_r = radial shrinkage from green to 10 per cent moisture content (per cent).

(b) Tangential shrinkage

$$S_t = \frac{T_g - T_a}{T_g} \times 100$$

where: T_g = tangential dimension green.
T_a = tangential dimension at 10 per cent moisture content.
S_t = tangential shrinkage from green to 10 per cent moisture content (per cent).

(c) Longitudinal shrinkage

$$S_l = \frac{L_g - L_o}{L_g} \times 100$$

where: L_g = longitudinal dimension green.
L_o = longitudinal dimension oven-dry.
S_l = longitudinal shrinkage from green to oven-dry (per cent).

8.3.4 Anatomical features

The laborious nature of assessing anatomical features by optical techniques for many years restrained researchers to conduct large scale studies in this field. Electronic and computer equipment nowadays available enables the rapid and accurate assessment of a wide variety of anatomical features on a large number of samples. Equipment of this kind enabled the candidate to study and measure the anatomical properties of *Eucalyptus grandis* and their relationships with growth stresses most efficiently.

Small sample blocks, approximately a cube with 6 to 8mm sides were prepared for microtome sectioning. Adjacent to these blocks, thin shivers (1mm thick) were split off parallel to the grain for the determination of fibre lengths.

Blocks prepared for anatomical studies on the cross-section and tangential section were softened by boiling in water, and sectioned by means of a sliding microtome to a thickness of 20 microns. The sections were stained with safranin and permanently mounted in Entellan rapid mounting medium.

Shivers for fibre length measurements were taken from the radial face of each block and macerated by heating in a 1 : 1 (v/v) mixture of glacial acetic acid and 30 per cent hydrogen peroxide at 60°C for 48 hours in small 10mm diameter glass phials. At the end of the delignification period, the maceration mixture was removed and the macerated sample was washed by distilled water. Fibre separation was obtained by shaking vigorously in water. A concentrated fibre slurry was obtained by sucking off the water through a glass tube fitted with fritted glass filter of fine porosity. The fibres were then washed thoroughly to ensure the complete removal of all traces of digestion chemicals. Finally ethyl alcohol (100%) was added, the mixture was again properly stirred, and sucked dry.

The fibres were stained by adding three drops of an alcoholic solution of safranin stain onto the fibre mat and allowed to react for a few minutes. Finally, the fibres were successively flushed and sucked dry with 50, 95 and 100 per cent ethyl alcohol and finally dehydrated with xylene.

After removing the xylene, excess fibres were removed leaving just enough for mounting. A few drops of Entellan rapid mounting medium, slightly diluted with xylene, were then added and the mixture slowly stirred for a few seconds to obtain a good dispersion of fibres. After checking the concentration of the fibres in the mixture, permanent mounts were prepared by transfering a few drops of the mixture to a microscope slide and covering it with a coverslip.

Preliminary studies were carried out to determine the number of measurements required (sample size) to yield an estimate of the mean within $\pm$ 3 per cent of the tree mean at the 95 per cent level of confidence. Calculations were based on data obtained from various pith-to-bark positions. The sample size was determined from a formula proposed by Davidson (1972):

$$n = (ct)^2/e$$

where: n = sample size required
t = the tabulated student's t for a set confidence level (a 0,95 confidence level was used)
e = error of the mean required (a 3 per cent error limit was used)
c = coefficient of variation

One hundred fibres per specimen were measured in the preliminary study to determine the within-slide variability in fibre length.

The coefficient of variation varied from 8 to 14 per cent. Calculations indicated that sample sizes varying from 25 to 84 would be adequate to provide an estimate of the mean fibre length within the error limit of 3 per cent. A standard sample size of 90 was therefore used to study fibre length variation. Two slides were prepared for each sample in order to ensure a large enough number of fibres for measurement.

8.3.4.1 Fibres

Each slide was projected onto a digitizer table connected to a H.P.1000 mini-computer. To ensure a complete, unbiased selection of fibres a 100mm diameter circle was drawn on the digitizer surface and used as sampling area. For the magnification used, the average fibre length equalled approximately one to one-half the diameter of the sampling area.

The lengths of all unbroken libriform fibres completely or partly within the sampling area were measured to the nearest millimetre on the projected image. For simplicity, all measurements were carried out at one magnification.

Any of the four corners of the coverslip was randomly chosen as a starting point for measurement. From this point the sampling field was moved diagonally to the adjacent area until the required number of fibres had been measured.

In addition to the fibre length measurements carried out on macerated samples, the relative proportion of fibre wall substance in the cross-section of the fibre was estimated. For this purpose a stereological counting technique, was followed (see Steel *et al.*, 1976).

Cross-sections were projected through a microscope onto a 13 x 13 square grid with a grid spacing of 5 x 5mm. Magnification was adjusted such that the projected image of the largest fibre was approximately equal to the grid spacing. The image was

rotated until the 169 grid intersection points were arranged symmetrically within the sampling field, in other words, the grid lines were parallel and perpendicular to the rays.

By taking each grid intersection as a sampling point, the number of sampling points coinciding with fibre walls and fibre lumens were recorded separately. Border-line grid points were alternatively assigned to cell wall and lumen.

Since considerable variation in the fibre cross-sectional properties occurred within each specimen, especially those originating from the outer parts of the stem, a minimum of ten sampling fields were selected at random within each specimen in order to obtain estimates reliable enough for comparisons among sampling positions and trees. This provided a minimum point count of at least 1 000 points. The total point count varied from specimen to specimen due to variations in the size and frequency of other tissue types present in the cross-section.

The data obtained provided a reliable estimate for the fractional wall volume (F_w) (sometimes referred to as the Mulsteph coefficient) and the fractional void volume (F_v) of fibres:

$$F_w = \frac{\text{Number of sampling points coinciding with fibre walls}}{\text{Total number of counting points coinciding with fibres}} \times 100$$

$$F_v = \frac{\text{Number of sampling points coinciding with fibre lumens}}{\text{Total number of counting points coinciding with fibres}} \times 100$$

To determine the average cross-sectional area of fibres, twenty counting fields, 100 micrometer long and 50 micrometer wide were selected at random and the number of fibres within each field counted. The length of the counting field was chosen such that the rows of fibre cells within the counting field could be considered as straight for all practical purposes. This was

fairly easy because the fibre cells in *Eucalyptus grandis* are characteristically arranged in radial rows (Figure 8.2). Counting fields were ignored, and a new counting field randomly selected, when anatomical features such as vessels, axial parenchyma and rays occurred in the counting field or obstructed the normal radial arrangement of fibres. Counting fields containing obvious fibres tips were also ignored. Mean fibre area for each sampling position was calculated as follows:

$$FA = \frac{\text{Total area of all counting fields}}{N}$$

where: N = total fibre cell count
FA = average cross-sectional area of fibre

Davidson (1972) devised five models of fibre cross-sections in order to study how the cross-sectional configuration of fibres would affect the cross-sectional fibre area, wall substance and lumen. Common terms were found among the models with only small differences as regard the multiplying constant.

Overall fibre diameter and lumen diameter were calculated using formulae based on a model considered by Davidson (1972) to represent the most common cross-sectional fibre configuration for *Eucalyptus deglupta*. This model, which treats both the fibre and lumen cross-section as hexagonal in shape, appears to be equally applicable to *Eucalyptus grandis* fibres (Figure 8.2):

$$D = \sqrt{FA/0,870}$$

where: D = average fibre diameter
FA = average cross-sectional area of fibre

$$L = \sqrt{LA/0,870}$$

where: L = average fibre lumen diameter
LA = average lumen area (= FA x $F_V/100$)

The following fibre properties were also calculated:

$$\text{Fibre flexibility coefficient} = \frac{\text{Fibre Lumen diameter (L)}}{\text{Fibre diameter (D)}}$$

$$= \sqrt{1 - F_W/100}$$

$$\text{Mean fibre wall thickness (W)} = \tfrac{1}{2}(D - L) = \tfrac{1}{2}D(1 - \sqrt{1 - F_W/100})$$

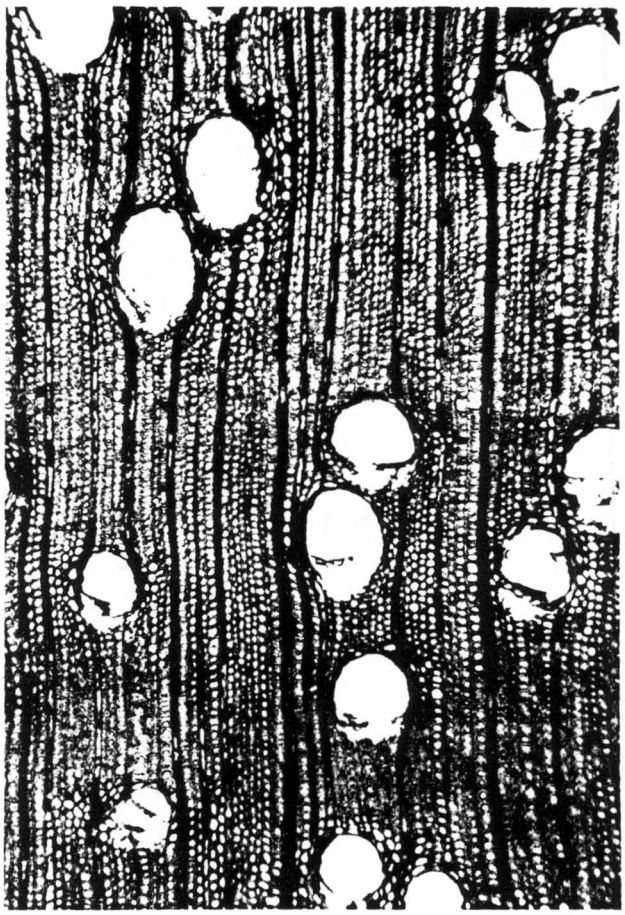
$$\text{Double-wall thickness (2W)} = D - L = D(1 - \sqrt{1 - F_W/100})$$

$$\text{Felting coefficient} = \frac{\text{Fibre length (FL)}}{\text{Fibre diameter (D)}}$$

$$\text{Runkel Ratio} = \frac{\text{Double-wall thickness (2W)}}{\text{Lumen diameter (L)}}$$

$$\text{Fibre density} = \frac{\text{Double-wall thickness (2W)}}{\text{Fibre diameter (D)}}$$

A



B

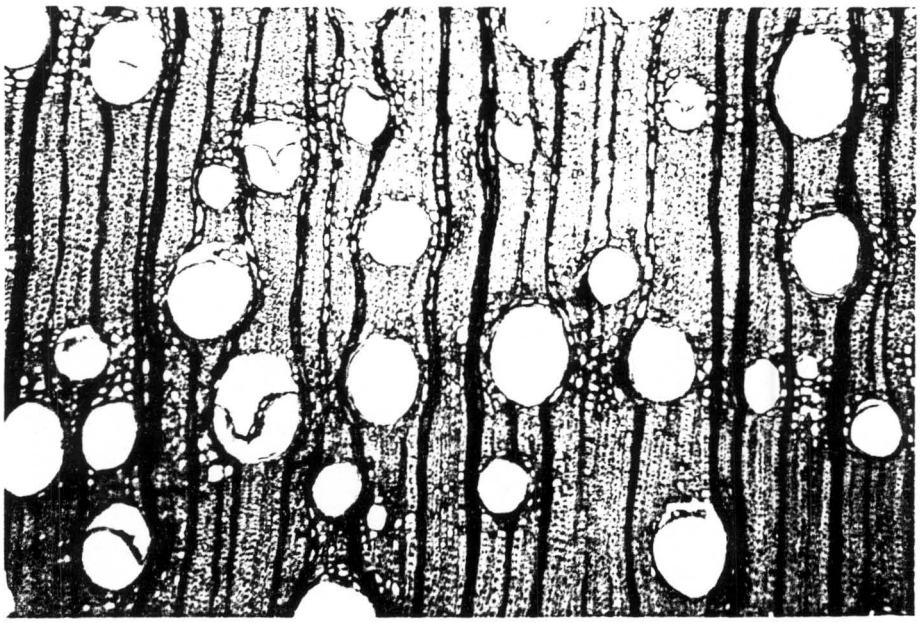
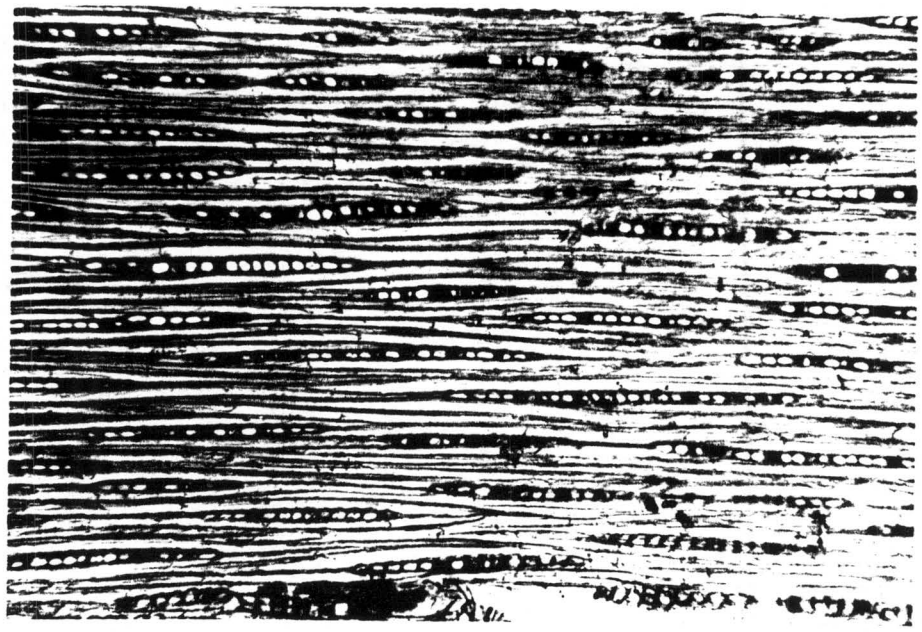
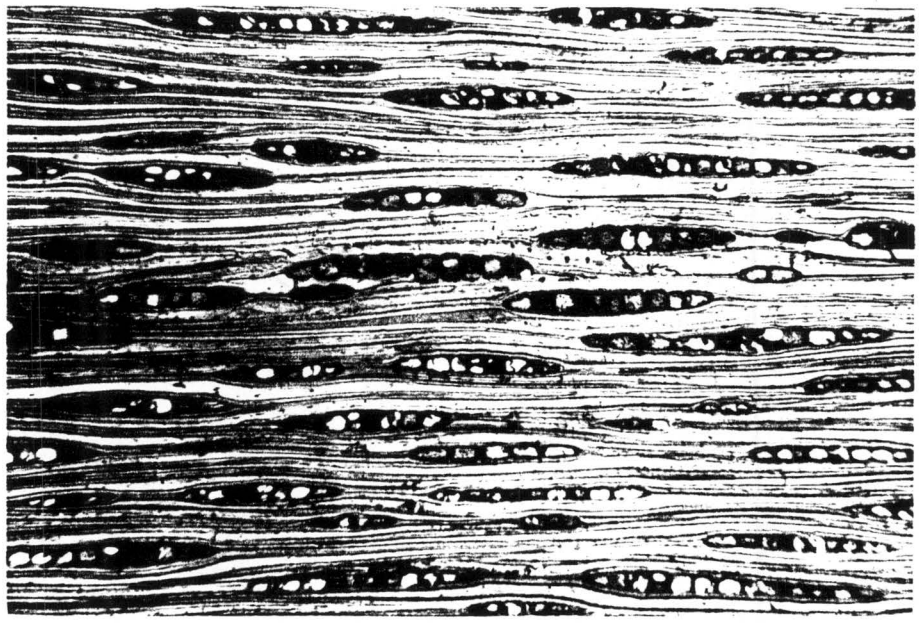


Figure 8.2: Cross-sections showing the difference in fibre-wall thickness in the sapwood of a low-stressed tree (A) and a high-stressed tree (B). (X40 magnification).



A



B

Figure 8.3: Tangential sections showing the difference in ray width between the inner (A) and outer (B) parts of the stem. (X100 magnification)

8.3.4.2 Vessels

Vessels are notably oval shaped with the longest axis in the radial plane. They are evenly distributed in the growth ring, almost always solitary and often arranged in oblique rows, especially in mature wood.

For the determination of the number of vessels per square millimeter (vessel frequency), a relatively low magnification was used which provided a large proportion of the specimen surface for counting. Five counting fields were selected at random covering a total area of about 18mm² of the specimen surface:

$$\text{Number of vessels per m}^2 = \frac{\text{Total number of vessels counted}}{18}$$

The tangential diameter of vessels was measured on a projected image of the cross-section on a digitizer table. Traverse lines running along the direction of growth from one edge of the cross-section to the other were selected at random. The diameter of all normal vessel cells coinciding with the traverse lines were measured. Underdeveloped vessel cells were ignored. A total of 90 vessel diameters were measured on each specimen and analyzed to study variations associated with level of stress and distance from the pith.

To estimate the percentage of the total volume of the wood occupied by vessels, random passes were made in the direction perpendicular to the direction of growth. Traverse lines were 1,890 micrometer in length and were randomly selected. At least 120 vessel cells were traversed in the tangential direction. Widths of vessel cells traversed were accumulated and a count was kept of the number traverses.

The percentage area of the cross-section occupied by vessels was calculated as follows:

$$\text{Percentage of vessel tissue in cross-section} = \frac{\text{Accumulated width of vessel tissue (in micrometer)}}{\text{Length of a single traverse x Number of traverses}}$$

Since vessels can be considered as continuous vertical tubes, this figure served as a reliable measure of the percentage of the total volume of the wood occupied by vessels (Davidson, 1972).

8.3.4.3. Rays

Ray width, number of rays per millimeter (ray frequency), and percentage of the total volume of wood containing rays, were determined on the tangential surface of the specimen.

Traverse lines were 740 micrometer in length and were selected on a random basis. At least 90 rays were traversed in the tangential direction. Again, widths of rays traversed were accumulated and a count was kept of the number of passes. All measurements were carried out on non-vessel areas of the tangential surface. Since the rays of this species are commonly uniseriate, a fairly accurate estimate could also be obtained of the mean ray width.

Since observations were carried out on vessel-free areas of the tangential surface, the following formula was applied to determine the percentage of total wood volume occupied by the horizontal system (see Davidson, 1972):

$$\text{Percentage volume of ray tissue} = \frac{\text{Accumulated width of ray tissue}}{740 \times \text{Number of traverses}} \times \frac{100 - \text{Vessel volume (\%)}}{100}$$

The number of rays per millimeter was obtained by dividing the total number of rays traversed, by the total traverse length.

8.3.4.4 Percentage fibres and axial parenchyma

Axial parenchyma of the species is predominantly paratracheal vasicentric and diffuse, and the amount present is relatively small. Near the pith it is extremely difficult to distinguish axial parenchyma cells from the surrounding thin-walled fibres cells which normally occur in the central part of the stem. For these reasons the determination of the fractional volume of this tissue type would have been extremely difficult and tedious. Fibres, vasicentric tracheids and axial parenchyma were, therefore, regarded as fibre tissue.

With both the percentage rays and percentage vessels known, the percentage of the wood made up of fibres tissue could be obtained by subtraction.

8.4 Results

8.4.1 Association between wood properties and level of growth stress within leaning trees.

Both leaning trees examined showed a considerable variation in the peripheral growth strain around the stem (Figure 8.4), the lowest values corresponding more or less to the under side (or leeward side) of the lean. In tree no. 2 the growth strain observed on the upper side (windward side) was about six times that on the opposite side.

8.4.1.1 Density variation.

In *Eucalyptus regnans* a close association was found between peripheral stress and the quantity and degree of thick-walled

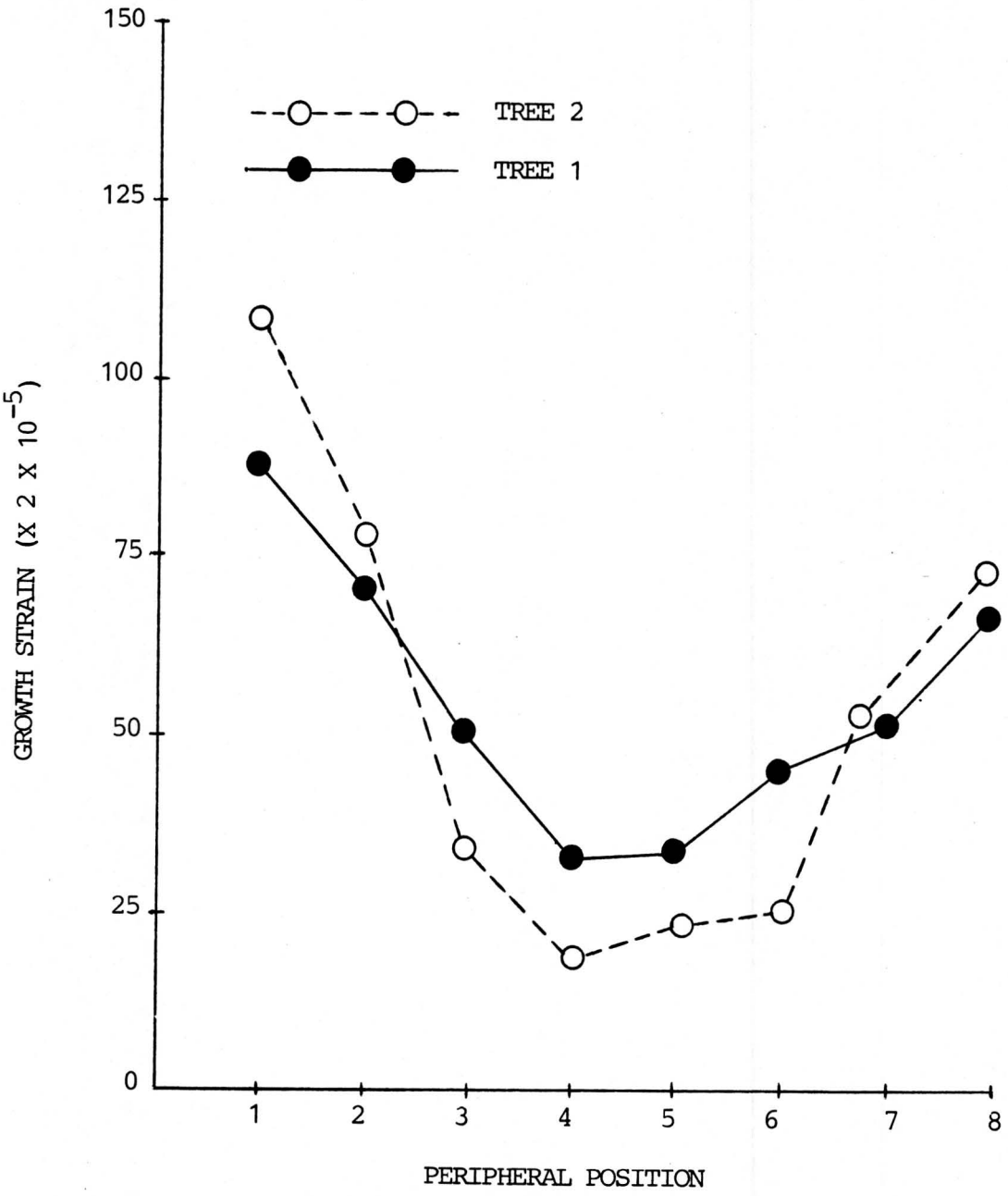


Figure 8.4:- Circumferencial growth strain variation on the surface of the stems of two leaning *Eucalyptus grandis* trees.

fibre cells. Variations in fibre cell structure in the outer layers of leaning trees largely accounted for the variation in physical wood properties observed. It was hypothesized that the formation of thick-walled cells is closely related to the trees' requirements for mechanical support and also serve as the basic mechanism to maintain or to change the spatial position of the tree in relation to neighbouring ones (Nicholson *et al.*, 1972).

In contradiction to what has been found for Australian grown *Eucalyptus regnans* (Nicholson *et al.*, 1972 and 1975), no relationship between peripheral growth strain intensity and the basic density of end-matching material was observed on the two leaning trees selected for this study (Figures 8.5 and 8.6). Since both trees examined in this study showed high density values at all positions sampled, it was hypothesized that these trees needed no additional mechanical support at positions corresponding to the upper side of the lean.

To test this hypothesis, an additional tree showing much lower density values on the underside of the lean, was examined. In this case a close association was observed between peripheral growth strain and basic density (Figure 8.7). From this result it appears that in leaning trees having a natural tendency to produce wood of lower overall density, and hence lower strength, there is a greater need to develop strengthening tissue to provide the required additional mechanical support at positions corresponding to the upper side of the lean. However, it still remains to be seen whether or not this phenomenon is maintained for a larger sample of trees.

8.4.1.2 Shrinkage variation

Radial, tangential, volumetric as well as longitudinal shrinkage increased with increased level of peripheral growth strain (See Figures 8.8 through 8.15).

The longitudinal shrinkage of normal wood is usually very small (on average about 0,23 per cent from green to oven-dry for mature *Eucalyptus grandis*. See van Vuuren *et al.*,1978) and can be neglected for most practical purposes. However, abnormal longitudinal shrinkage often occur in certain types of wood. In tension wood longitudinal shrinkage may be as much as five times greater than in normal wood.

Although the increase in longitudinal shrinkage of tension wood over normal wood is directly related to the proportion of gelatinous fibres present (Arganbright *et al.*, 1970; Patel, 1964; Perem, 1964, as reported by Panshin and de Zeeuw, 1980), it is unlikely that the gelatinous fibres can have a direct effect on longitudinal shrinkage. This is because the microfibrils in the gelatious layer run almost parallel to the longitudinal axis of the cell and also form a poor bonding with the rest of the secondary wall. The increased longitudinal shrinkage in tension wood must, therefore, be associated with changes that take place in the average microfibrillar angel in the S1- and especially the thick S2-layer of the secondary wall. In tension wood the average microfibrillar angle is large with respect to the longitudinal axis of the cell as opposed to the small average angles in normal wood, causing an increased longitudinal shrinkage component to the wood.

In the study trees radial and tangential shrinkage showed a tendency to increase with an increase in growth strain level. In theory this should be exactly opposite because of the positive relationship between stress and longitudinal shrinkage observed. Although most of the relationships were poor, even after ignoring outliers, definite trends existed which cannot be explained in terms of generally accepted changes in the direction of microfibrillar orientation in the various secondary wall layers as a result of changes in the level of growth stress.

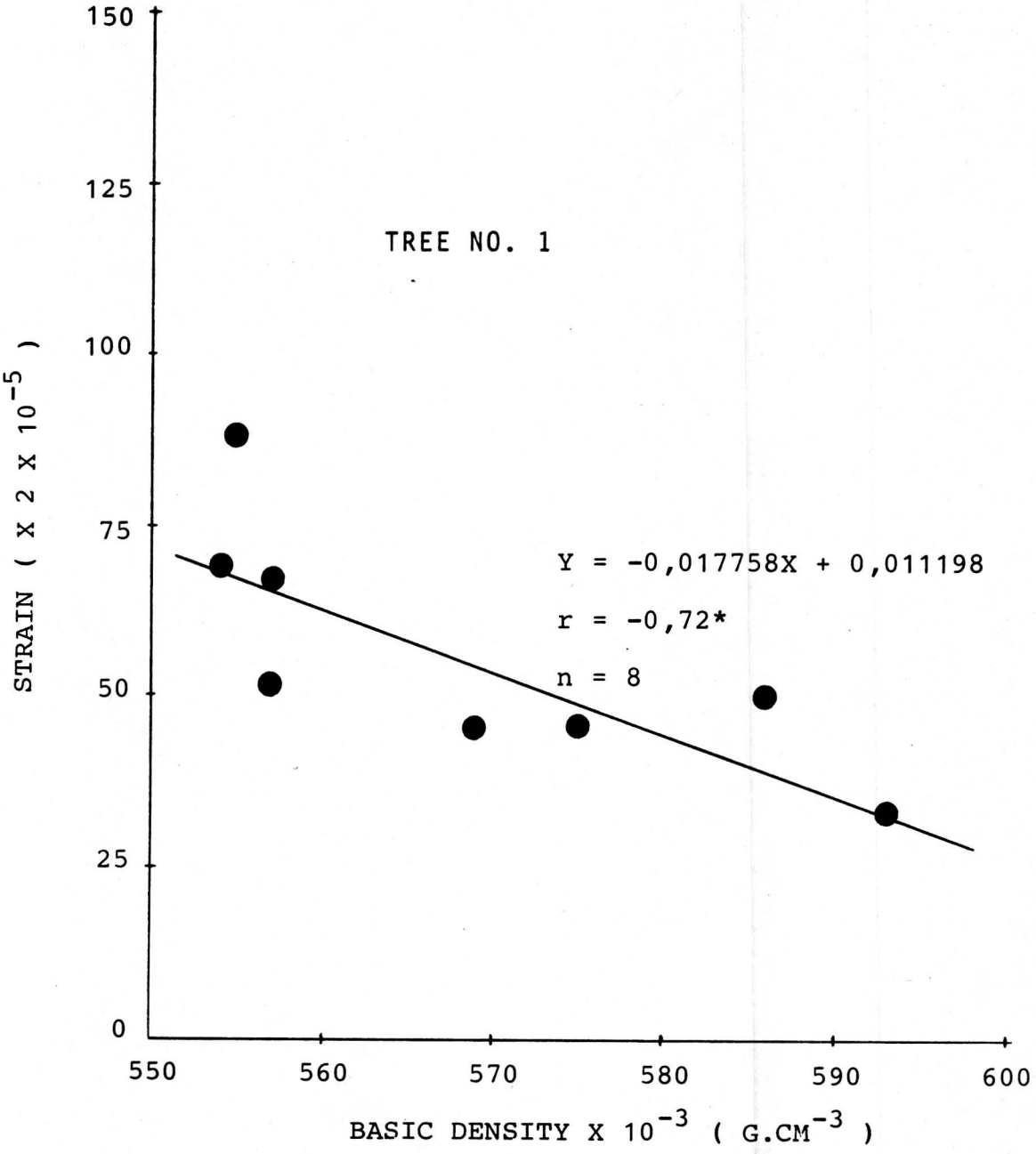


Figure 8.5:- Relationship between surface strain and basic density.

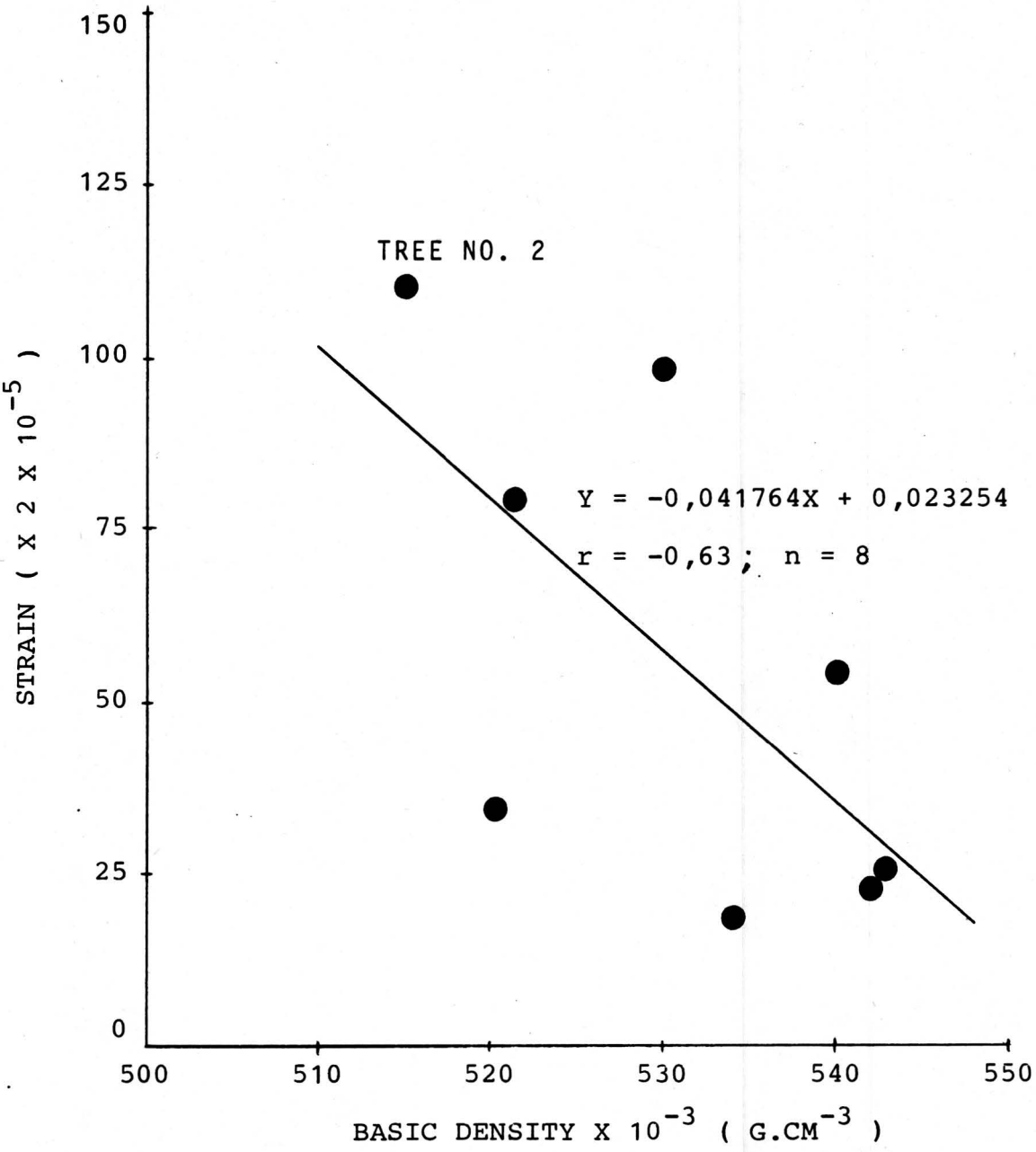


Figure 8.6:- Relationship between surface strain and basic density.

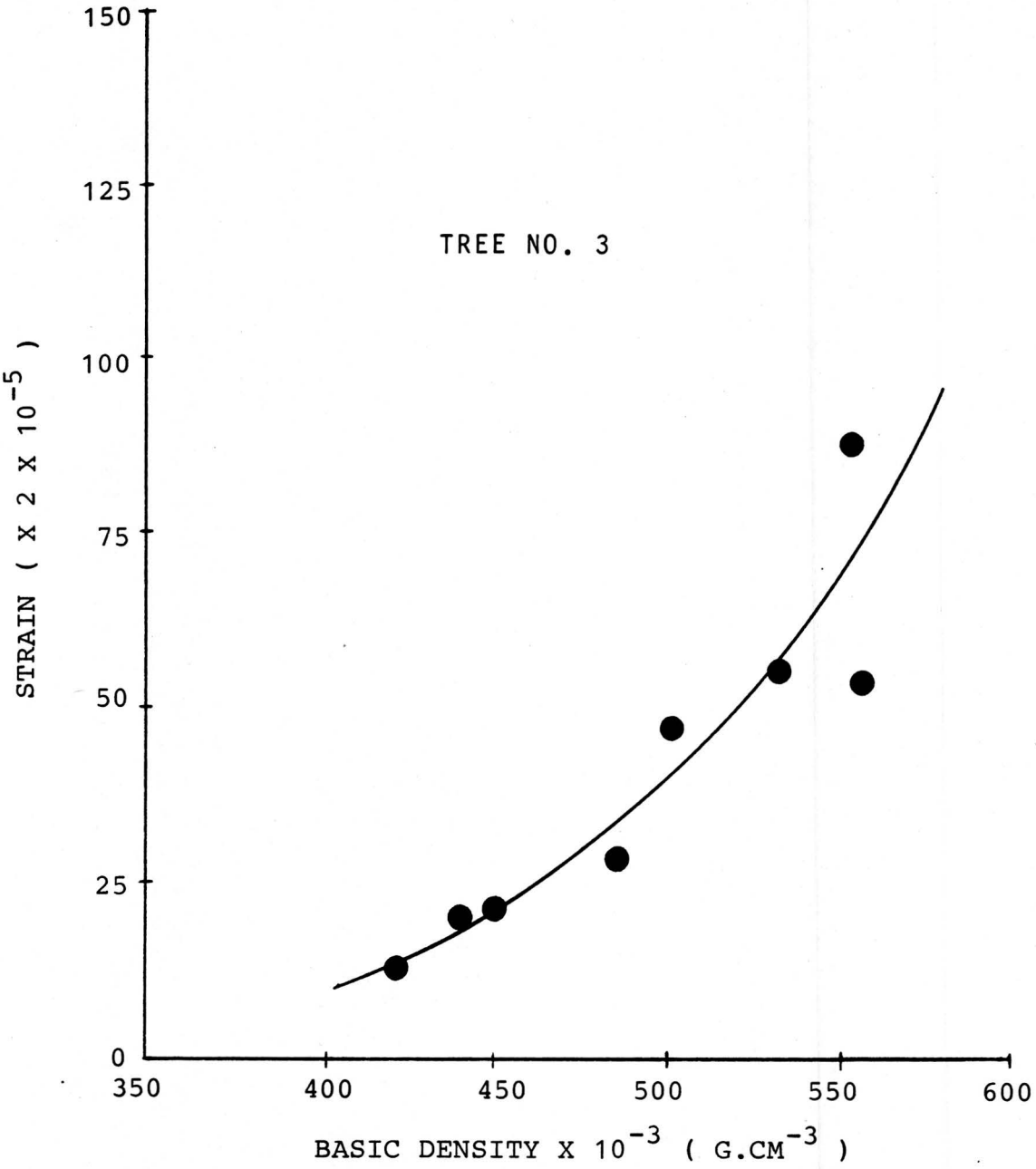


Figure 8.7:- Relationship between surface strain and basic density. Curve is hand drawn through data points.

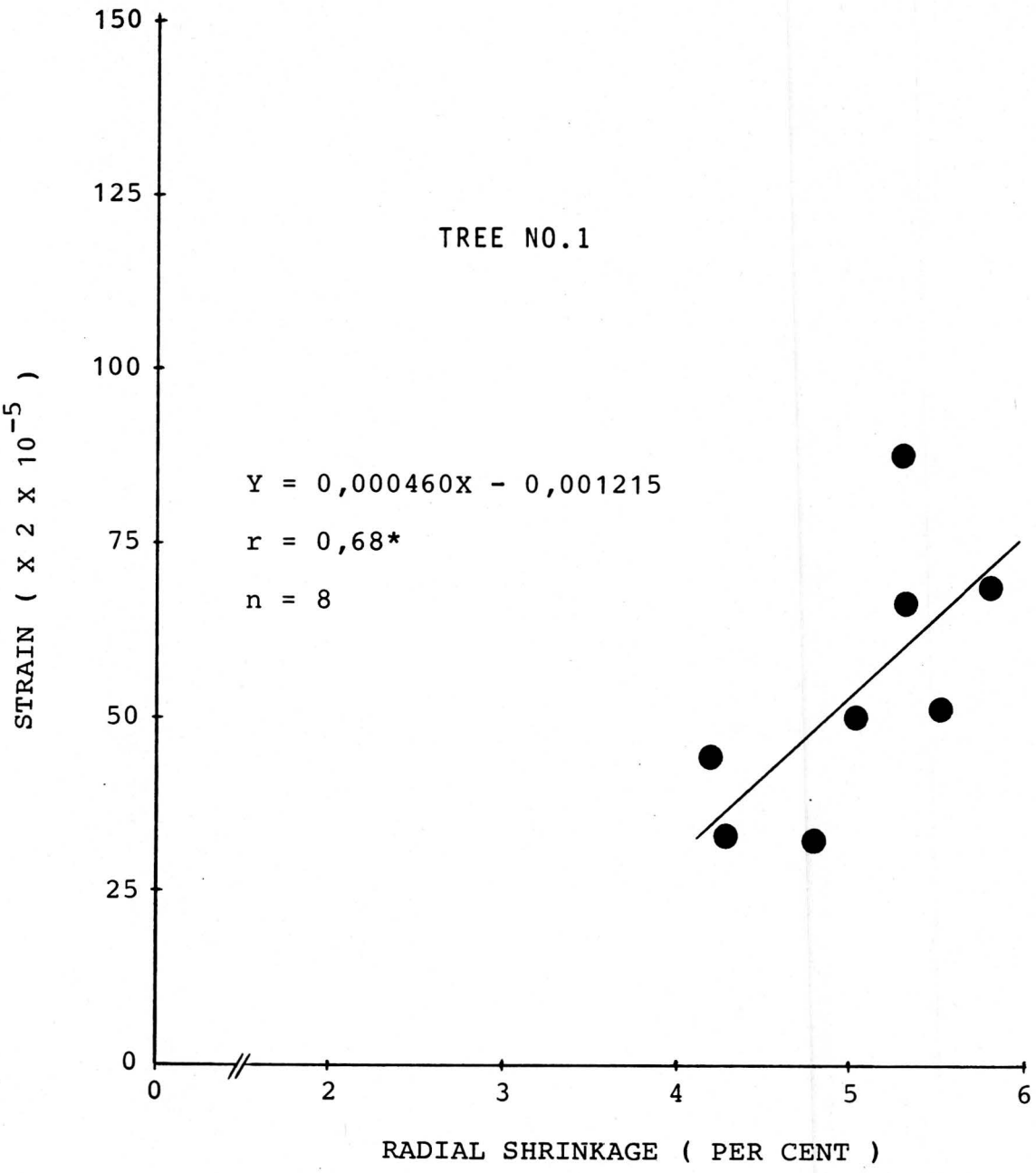


Figure 8.8:- Relationship between surface strain and radial shrinkage from green to 10 per cent moisture content.

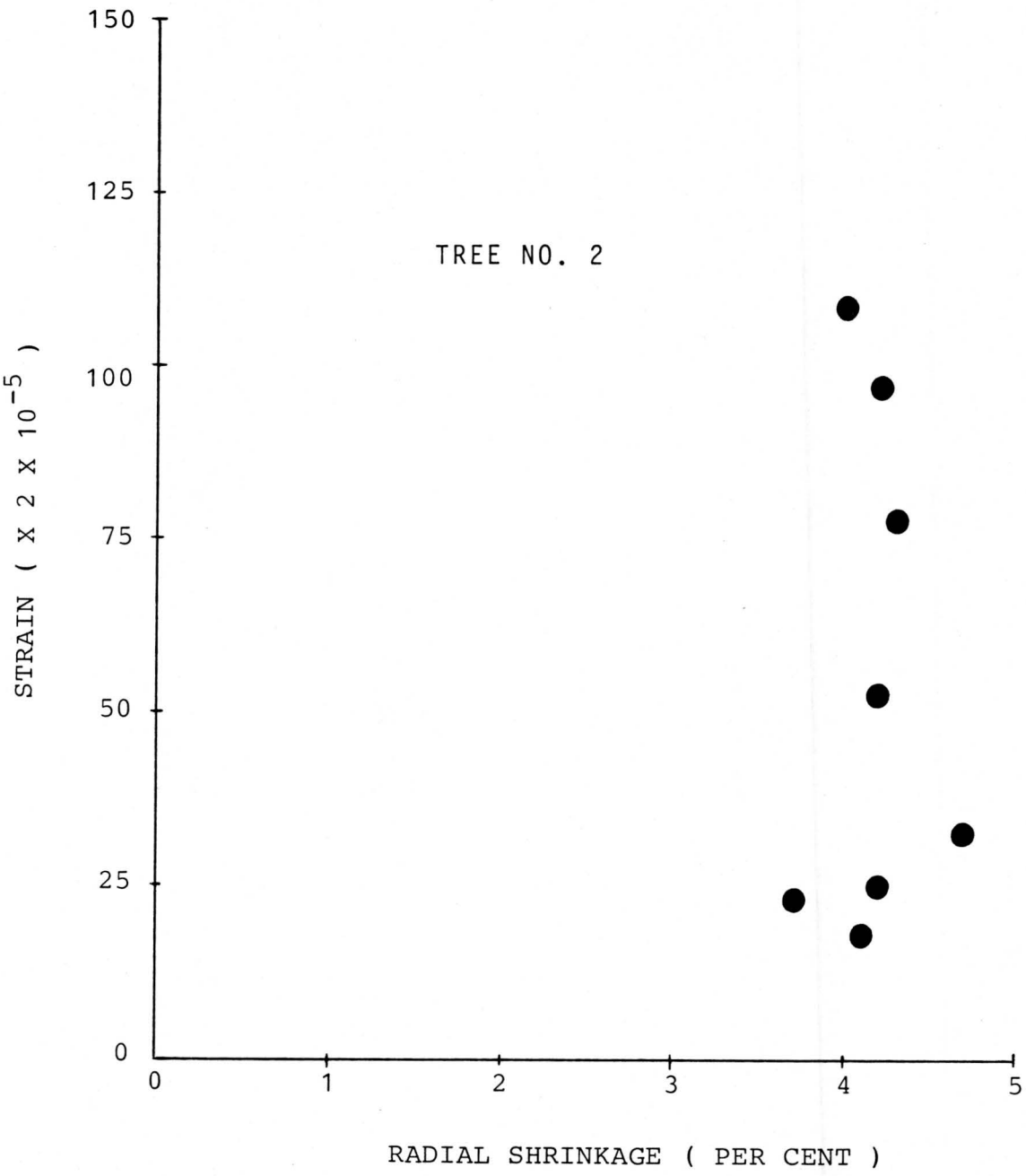


Figure 8.9:- Relationship between surface strain and radial shrinkage from green to 10 per cent moisture content.

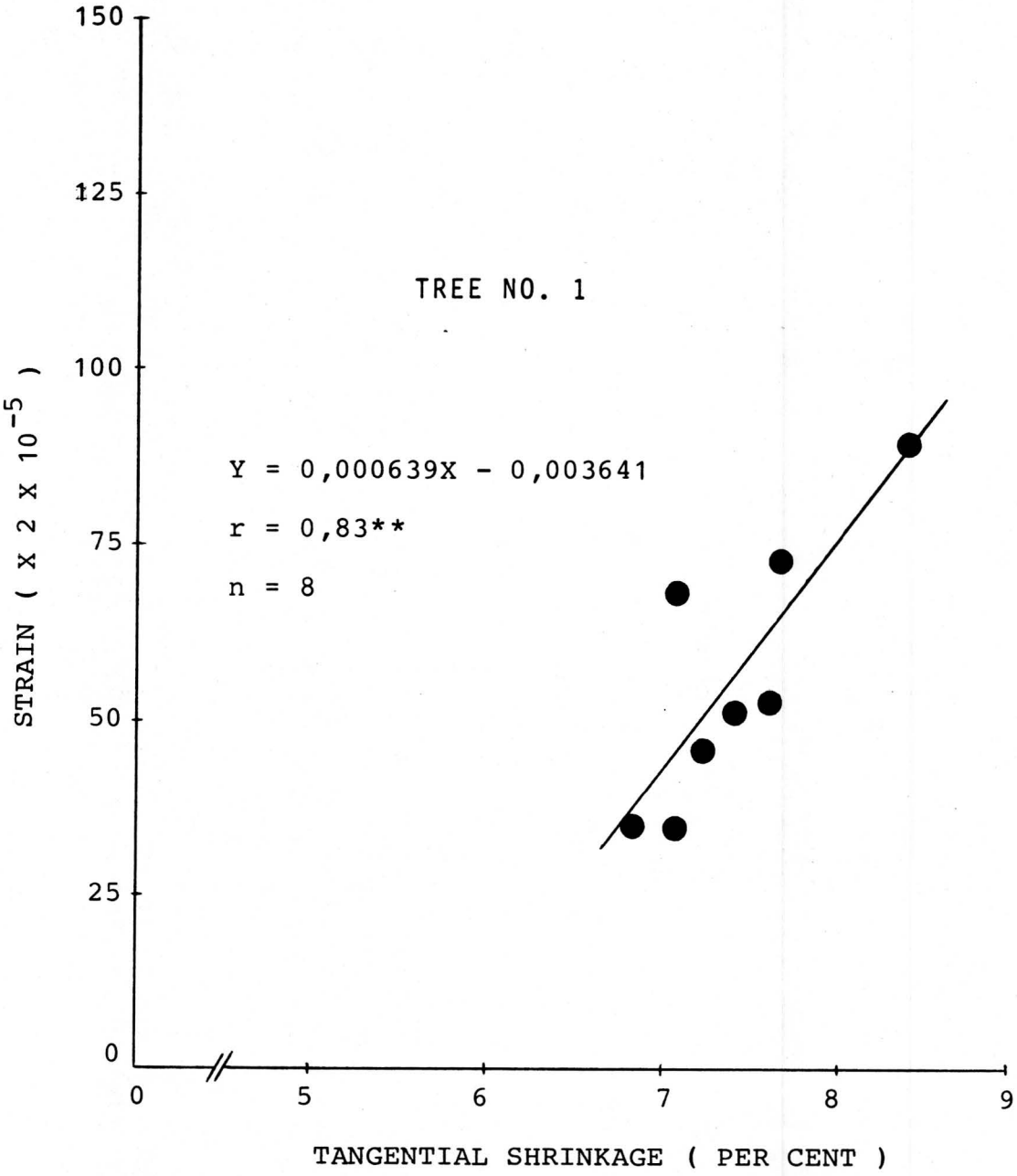


Figure 8.10:- Relationship between surface strain and tangential shrinkage from green to 10 per cent moisture content.

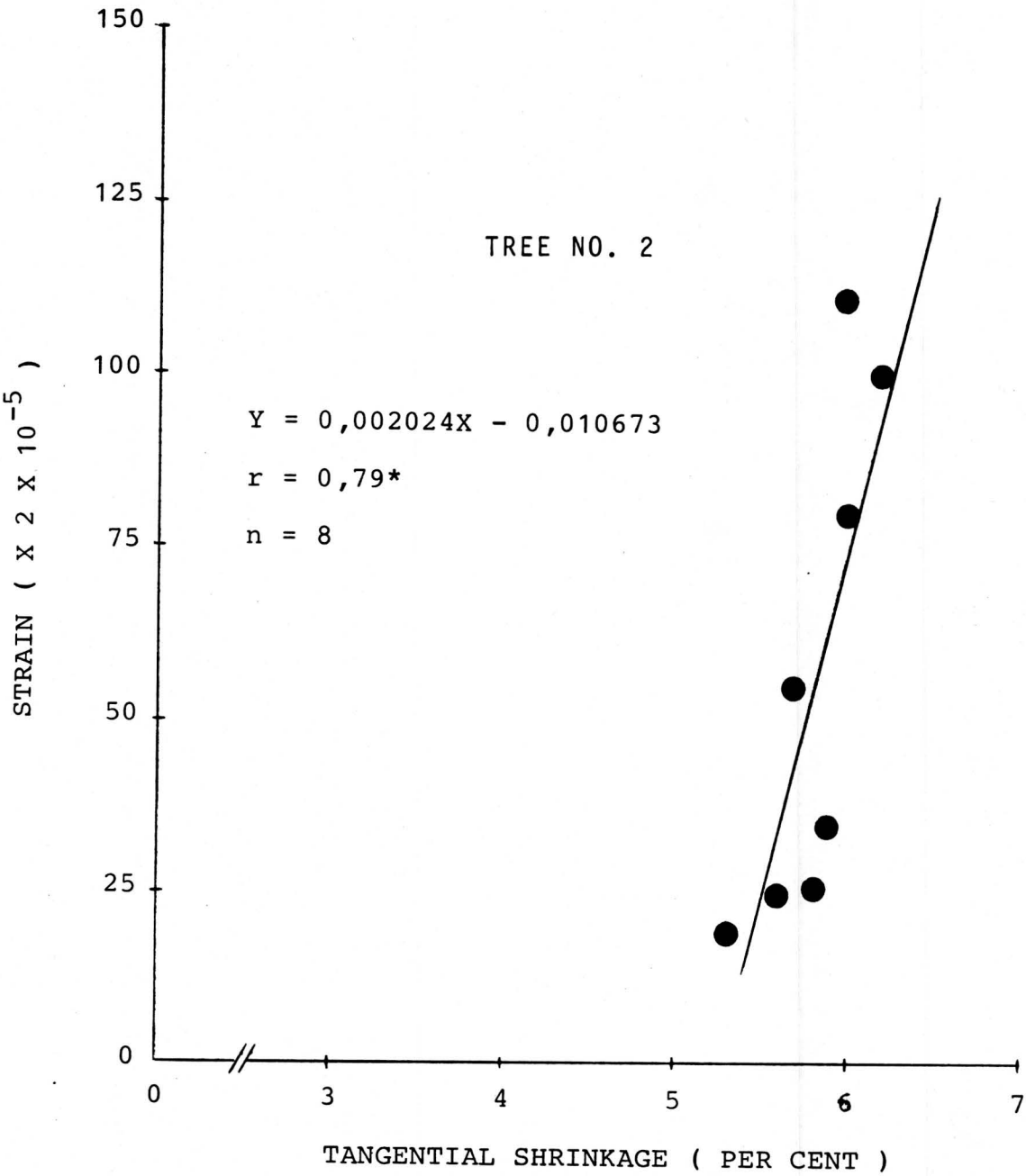


Figure 8.11:- Relationship between surface strain and tangential shrinkage from green to 10 per cent moisture content.

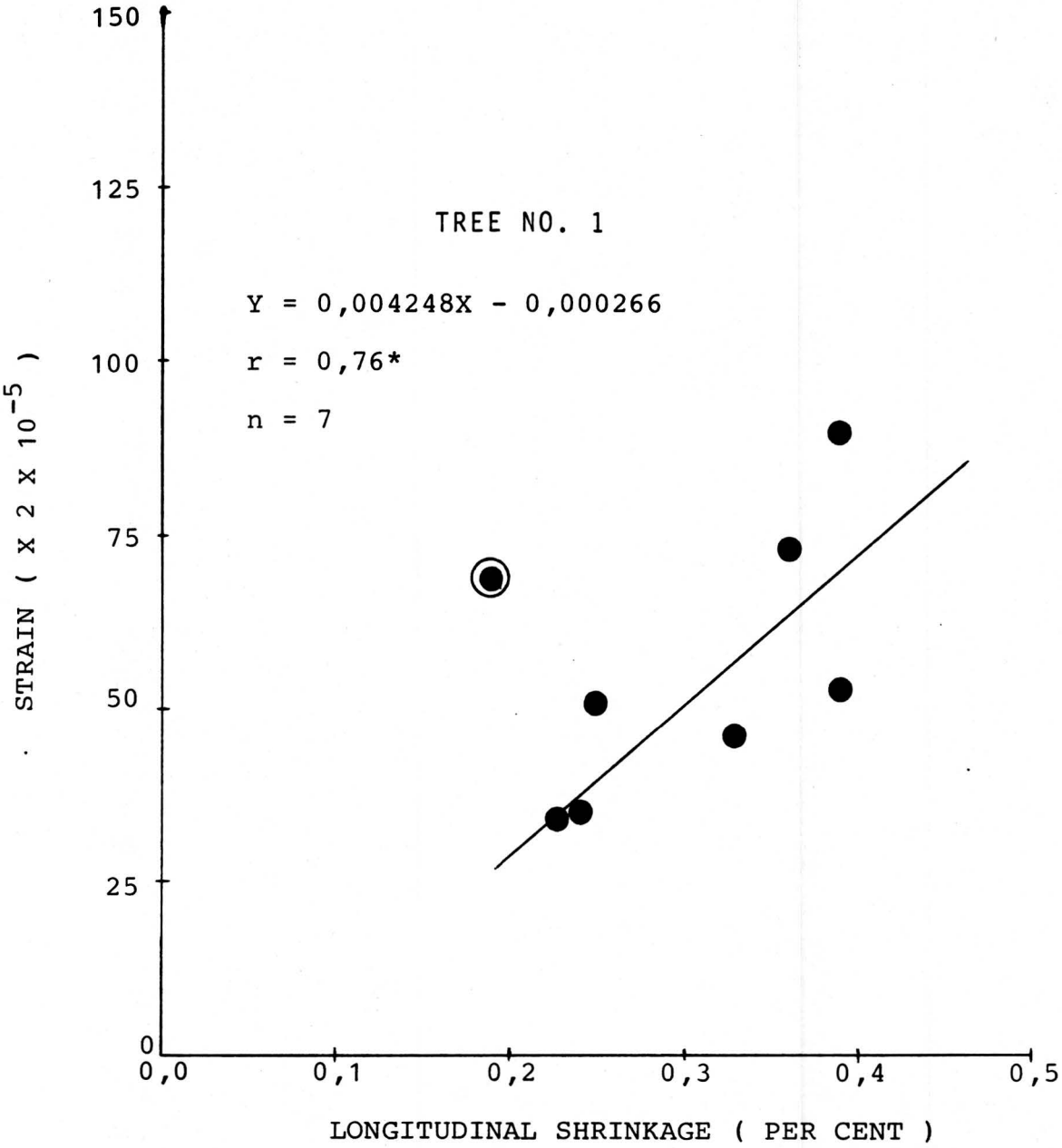


Figure 8.12:- Relationship between surface strain and longitudinal shrinkage from green to oven-dry

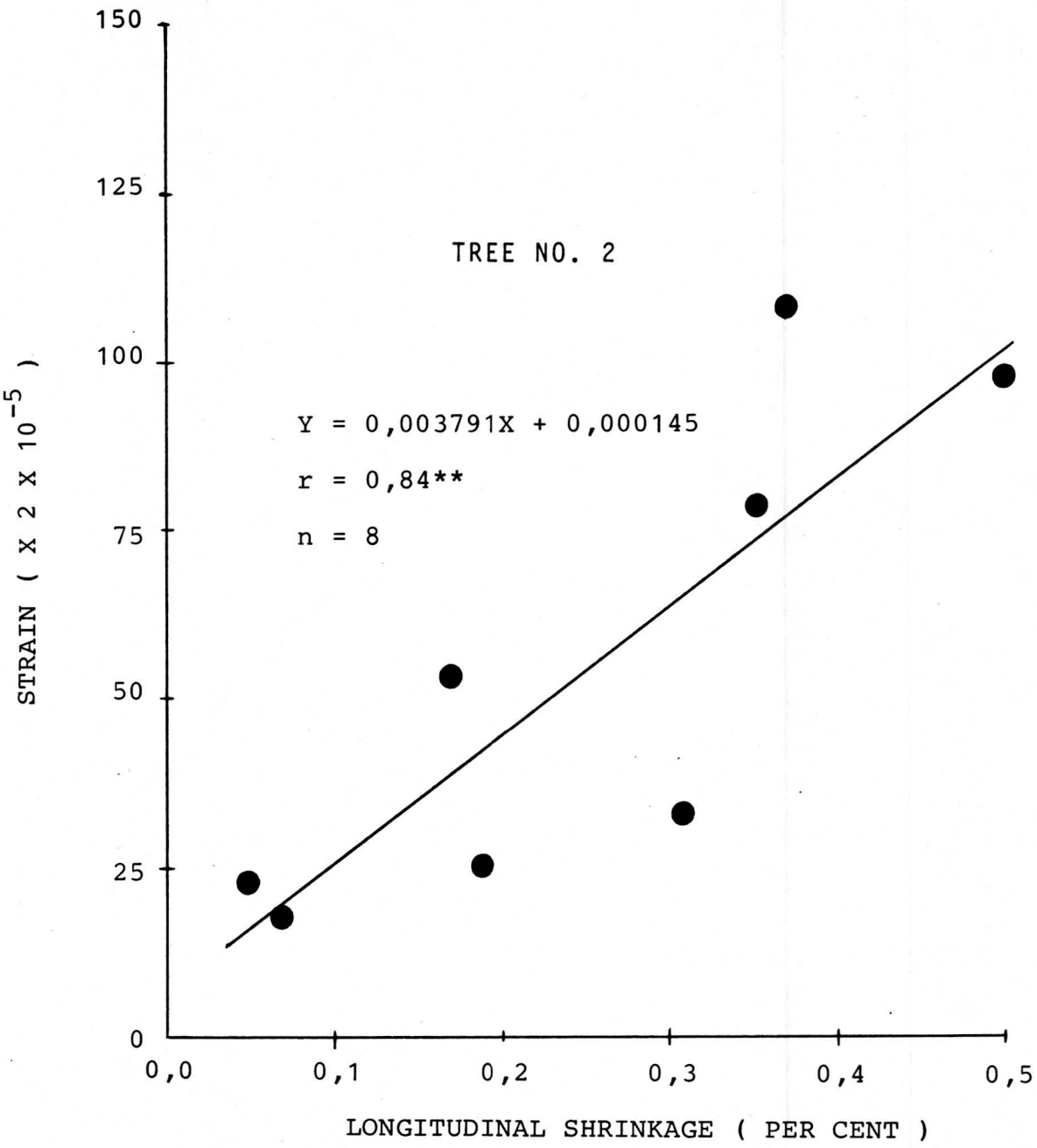


Figure 8.13:- Relationship between surface strain and longitudinal shrinkage from green to oven-dry

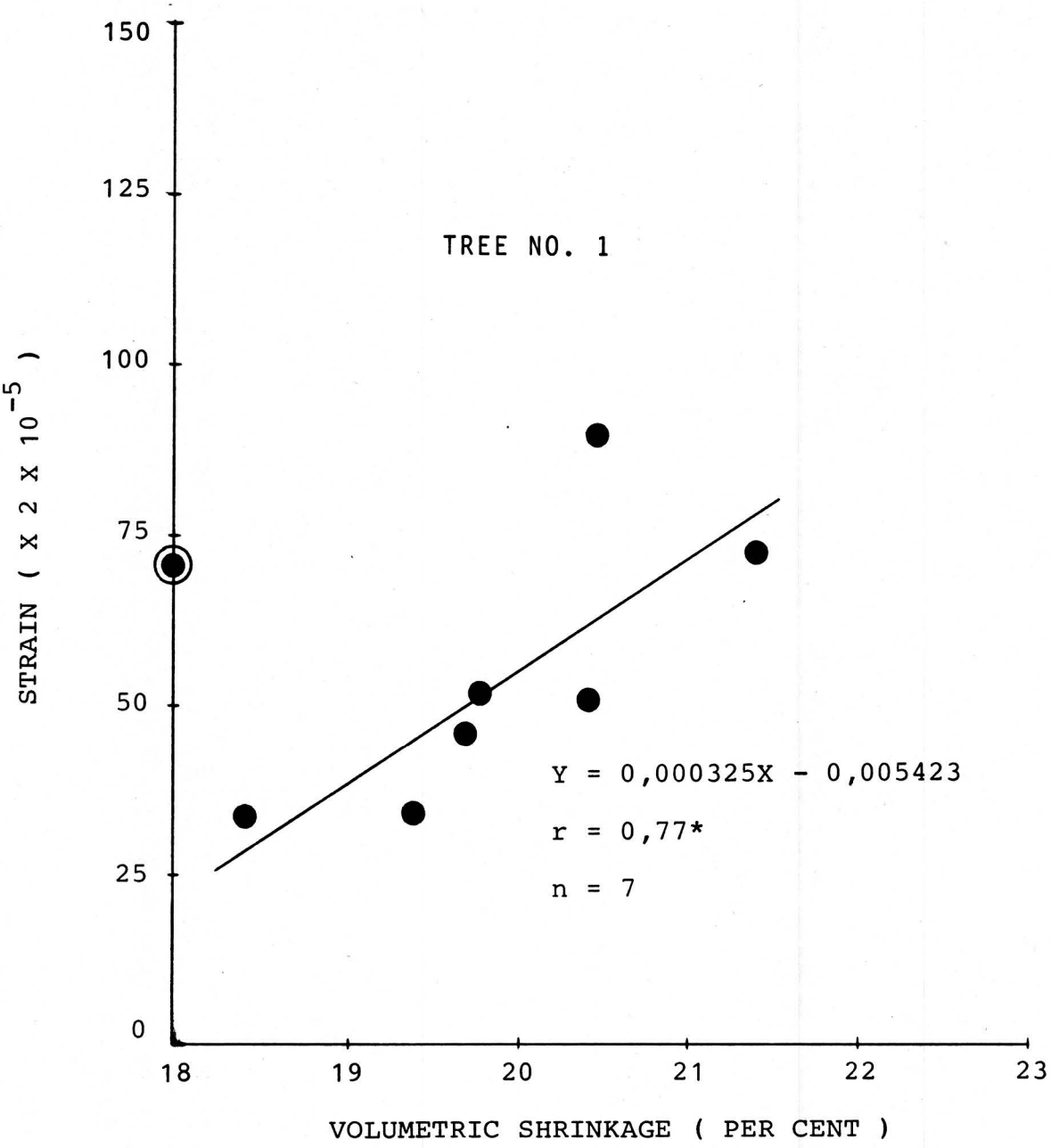


Figure 8.14:- Relationship between surface strain and longitudinal shrinkage from green to oven-dry

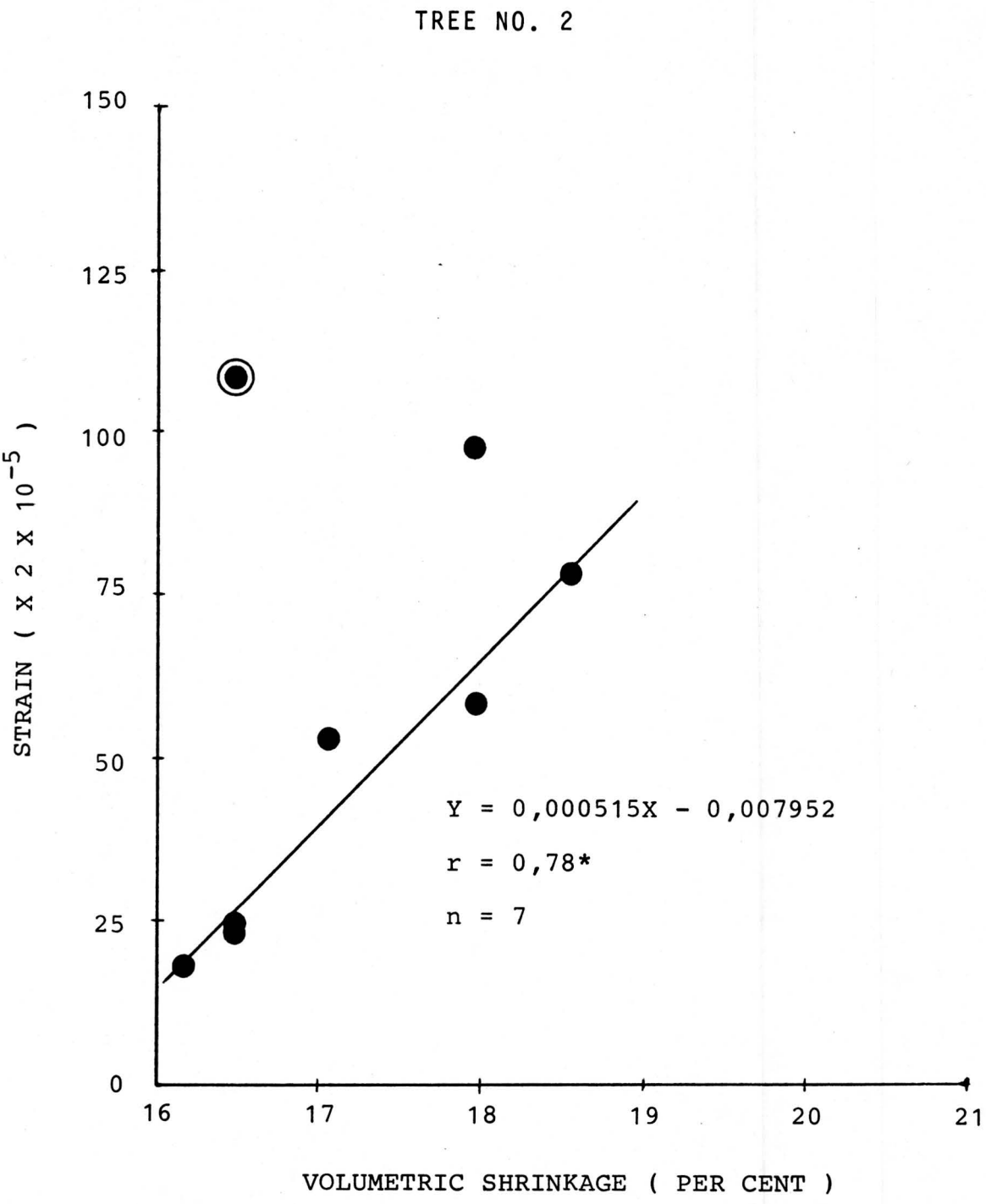


Figure 8.15:- Relationship between surface strain and longitudinal shrinkage from green to oven-dry.

Volumetric shrinkage is usually a direct function of basic density, which means that the specific shrinkage (ratio of volumetric shrinkage to basic density) should be more or less constant for a species (Perem, 1964). A comparison of specific shrinkage values computed for the various growth strain positions are presented in Table 8.2. Contrary to findings by Perem (1964) on five Canadian hardwoods, specific shrinkage appeared to be higher in areas of high stress.

8.4.1.3. Variation in fibre characteristics

In the two study trees, fibre length increased with increasing level of peripheral growth strain (Figure 8.16). The relationship between peripheral strain and fibre length was particularly marked in Tree no.1. In Tree no.2 the association appeared to be less pronounced in spite of the greater range of variation in peripheral growth strain that occurred in this tree (see Figure 8.4). Even though the relationships were found statistically non-significant, the results nevertheless imply that fibres tend to be longer in high-stressed areas than in low-stressed areas within the same tree.

Variation in fibre diameter around the stem did not exhibit a pattern which showed a close linkage with the variation in peripheral growth strain. However, in both trees fibre diameter was significantly larger on the low-stressed side of the stem.

Obtaining a reasonable accurate estimate of fibre cross-sectional properties in leaning trees was an extremely difficult and tedious task. Definite zones of tension wood occurred in the cross-section among normal fibres. Although no quantitative assessment was made of the size and frequency of these zones of tension wood at each position, they appeared more prominent as regards their size and wall-thickness in areas subjected to high stress levels.

Table 8.2:- Variation in shrinkage of test specimens originating from different peripheral positions in leaning trees.

Tree No.	Peripheral Growth Strain ($\times 2 \times 10^{-5}$)	Radial Shrinkage (per cent)	Tangential Shrinkage (per cent)	Longitudinal Shrinkage (per cent)	Volumetric Shrinkage (per cent)	Basic density ($g.cm^{-3} \times 10^{-3}$)	Specific Shrinkage
1	88	5,3	8.4	0,39	20,5	554	37,00
	71	5,8	7,7	0,36	21,4	553	38,70
	50	5,0	7,4	0,25	20,4	586	34,81
	33	4,8	7,1	0,23	18,4	596	30,87
	34	4,3	6,8	0,24	19,4	569	34,09
	45	4,2	7,2	0,33	19,7	575	34,26
	51	5,5	7,6	0,39	19,8	558	35,48
	67	5,3	7,1	0,19	18,0	557	32,31
2	109	4,0	6,0	0,37	16,5	515	32,04
	78	4,3	6,0	0,35	18,6	521	35,70
	33	4,7	5,9	0,31	18,0	520	34,62
	18	4,1	5,3	0,07	16,2	534	30,34
	23	3,7	5,6	0,04	16,5	542	30,44
	25	4,2	5,8	0,19	16,5	543	30,39
	53	4,2	5,7	0,17	17,1	549	31,15
	98	4,2	6,2	0,50	18,0	538	33,46

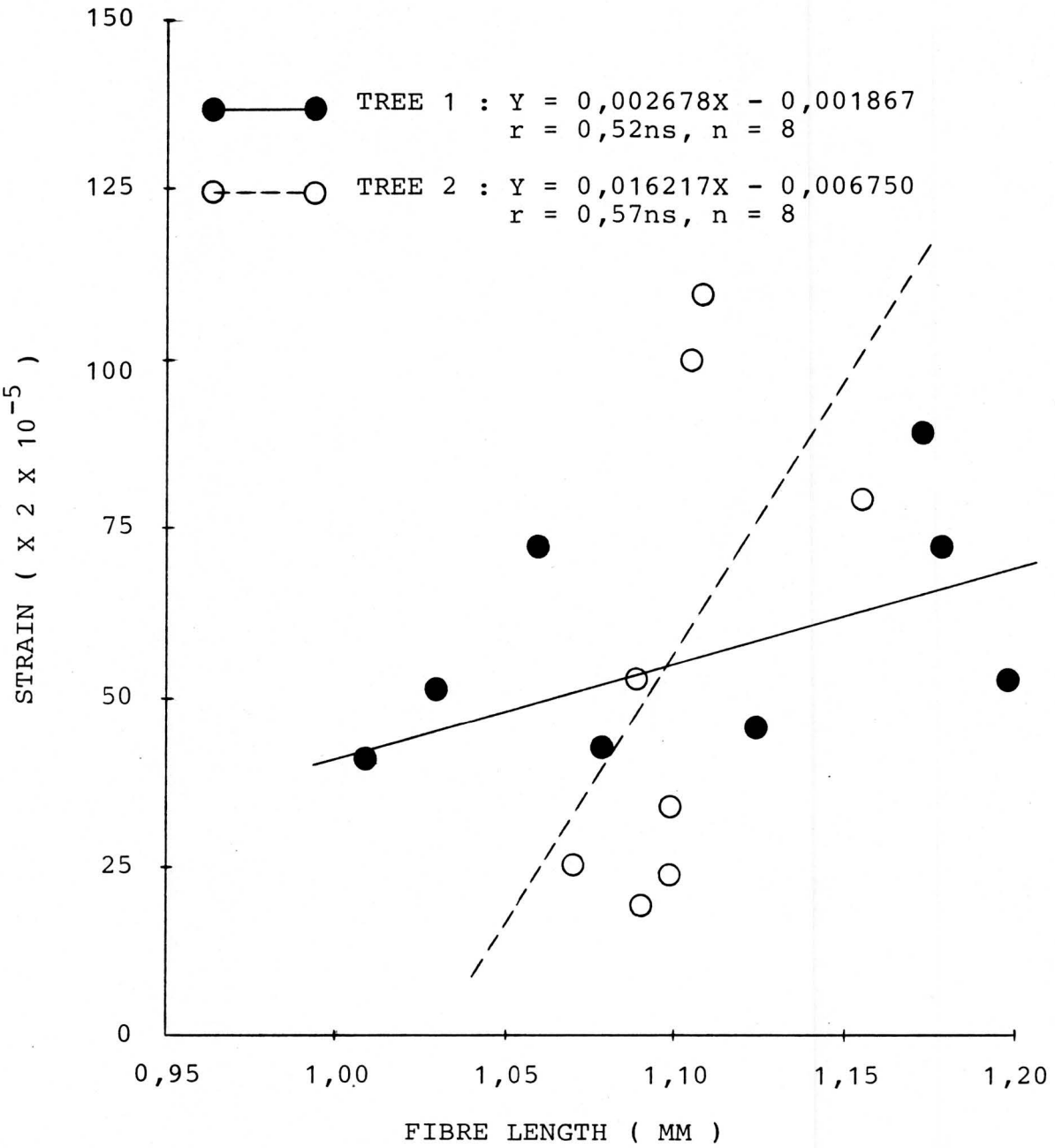


Figure 8.16:- Relationship between surface strain and fibre length in two leaning *Eucalyptus grandis* trees. Each data point is an average of at least 90 measurements.

8.4.1.4. Variation in vessel characteristics.

An association was found between stress intensity and tangential diameter of vessels (Figure 8.17). Vessel diameter was significantly smaller in regions of low stress in both the trees examined.

Vessel frequency fluctuated considerably around the stem. Although no clear pattern could be observed, the number of vessels per unit area appeared to be slightly less in the high-stressed areas of the stems.

It must be emphasized that in the zones of tension wood that occurred in varying degrees in the cross-sections examined, vessels were smaller in diameter and much less frequent.

This is an agreement with studies on tension wood in Yellow Poplar (Barefoot, 1965), Beech (Chow, 1946), Salix (Höster, 1972) and *Populus deltoides* (Kaeiser and Boyce, 1965).

8.4.1.5. Variation in ray characteristics

Considerable variation in ray width and ray volume occurred between peripheral positions, but there were no obvious patterns of variation showing any direct association with the variation in peripheral growth strain. However, ray width and ray volume values recorded at the lowest stress positions were significantly greater than those recorded at the upper side of the lean. Average values are given in Table 8.3.

Although differences in ray frequency occurred between the upper and lower side of the lean, these differences were small and non-significant (Table 8.3).

8.4.2. Association between wood properties and level of growth stress between trees.

Extreme differences in growth stress intensity occurred among the

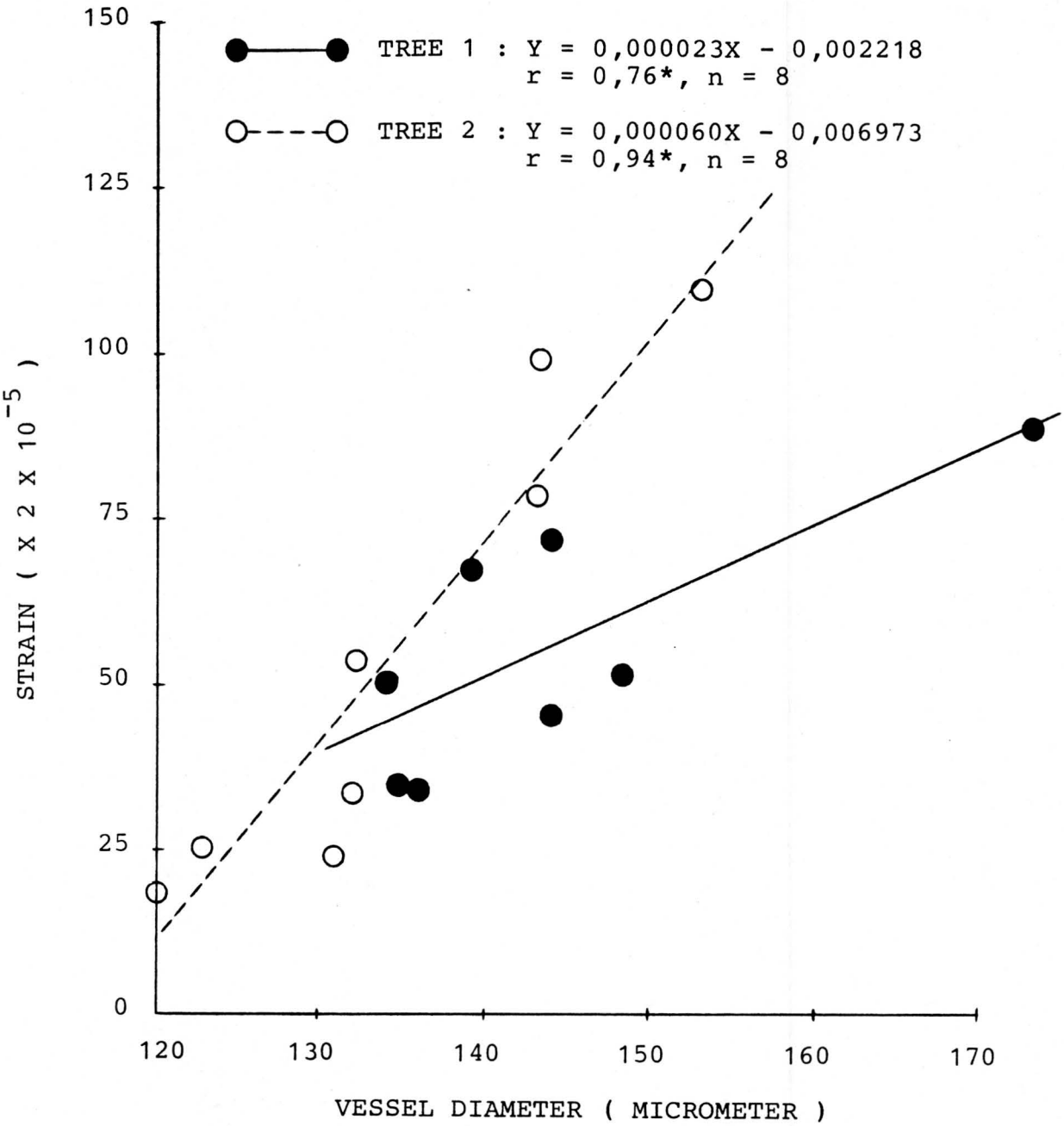


Figure 8.17:- Relationship between surface strain and tangential diameter of vessels in two leaning *Eucalyptus grandis* trees. Each data point is an average of 90 measurements.

Table 8.3:- Ray characteristics of wood from the upper and lower sides of two leaning *Eucalyptus grandis* trees.

Tree number	Sampling position	Rays per mm (Ray frequency)	Ray volume (per cent)	Ray width (micrometer)
1	Upper	12,77	16,80	15,75
	Lower	12,67	18,30	16,85
2	Upper	11,35	16,10	16,13
	Lower	11,80	20,70	20,03

30 vertical trees sampled in Compartment B26 in Wilgeboom State Forest for this investigation. Mean tree score values for splitting varying from 1,3 up to more than 6 were recorded. One tree exhibited an average split score of more than 13 (Figure 8.18). The material thus provided a good opportunity to study the properties of wood among vertical tree showing varying intensities of growth stress.

8.4.2.1. Stem characteristics

An attempt was made to relate level of growth stress with some stem parameters; all of which are strongly associated with wood quality and product yield. These were heartwood content, pith eccentricity, stem ovality and taper.

To study the association between these variables and growth stress level, the trees sampled were classified into three stress classes. The lower class represented trees showing virtually no splitting, except for two or three type A splits (low-stressed trees), while the upper class comprised trees showing extremely high split values (high-stressed trees). The rest of the sample was classified as medium-stressed trees.

Although the grouping of the thirty trees into three distinct growth stress classes resulted in an upper class exhibiting an average amount of splitting nearly four times that of the lower class, the means for the four stem parameters considered remained virtually the same (Table 8.4). Statistical comparisons of the mean values indicated that the slight differences that occurred were most likely due to chance.

8.4.2.2. Wood density

Ten trees were selected from the sample of thirty trees, to study the relationship between the level of growth stress and the properties of the wood. This was done so that two extreme stress classes (each containing five trees) could be obtained.

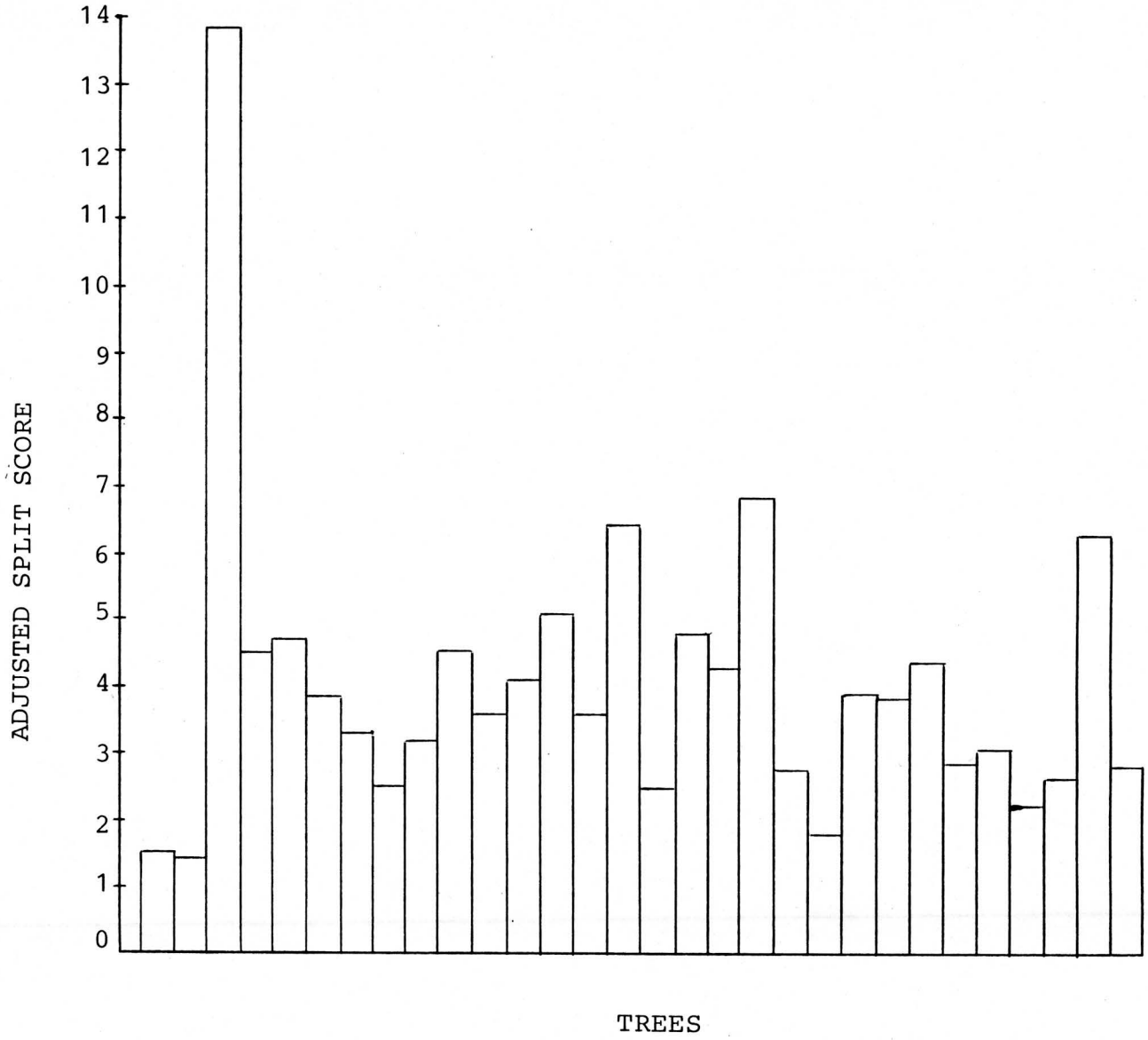


Figure 8.18:- Between-tree variation in mean log end-splitting.

Table 8.4:- Comparison of a number of stem characteristics on low-, medium-, and high-stressed *Eucalyptus grandis* trees sampled in the North-Eastern Transvaal.

Variable	Height above ground level (m)	Level of growth stress		
		Low (n=14)	Medium (n=11)	High (n=5)
D.B.H. OB (mm)	1,300	414	435	430
Taper per metre	-	6,70	5,37	6,00
Eccentricity	1,300	1,26	1,23	1,22
Eccentricity	5,075	1,18	1,20	1,15
Eccentricity	8,850	1,23	1,22	1,13
Eccentricity	12,550	1,19	1,18	1,17
Tree average	-	1,16	1,15	1,13
Ovality	1,300	1,12	1,15	1,12
Ovality	5,075	1,09	1,08	1,08
Ovality	8,850	1,11	1,08	1,09
Ovality	12,550	1,09	1,07	1,07
Tree average	-	1,11	1,09	1,09
Heartwood %	1,300	86,5	87,0	87,0
Heartwood %	5,075	85,8	85,4	86,4
Heartwood %	8,850	85,5	85,1	85,2
Heartwood %	12,550	84,1	83,8	84,1
Tree average	-	85,6	85,1	85,7
Splitting	1,300	1,34	1,45	3,74
Splitting	5,075	1,57	2,51	8,38
Splitting	8,850	1,63	2,50	5,04
Splitting	12,550	1,54	2,46	3,84
Tree average	-	1,54	2,32	5,72

From the discs cut at 1,3m and 5,1m height above ground level (see 8.2.2), wedges measuring about 50mm at the stem surface, were prepared along and perpendicular to the longest radius. As this species does not produce well defined annual rings, the wedges were proportioned into five radial segments of equal length. This was done so that pairs of wood specimens could be obtained which were formed in more or less similar periods of growth.

The density of each specimen prepared was determined on a green-volume and oven-dry-weight basis in accordance with the method described in subsection 8.3.1. No weighting was considered necessary because the segments prepared from the wedges were proportional to the increase in volume of wood from the pith outwards.

Variations in basic density among high- and low-stressed trees were examined by means of a three-way analysis of variance. The effect of level of stress, radius and radial position as well as their interactions were tested. Height above ground level could not be included in the model because the various pith-to-bark positions were not directly comparable. An analysis of variance was therefore carried out for each height separately (Table 8.6). The basic density data is summarized in Table 8.5.

Since some degree of pith eccentricity occurred in all discs cut from the study trees, there were differences on the length of wedges cut from the two radii. Results of the statistical analysis indicated no significant differences in basic density among the two radii (Table 8.6). Unweighted basic densities for the two radii are summarised in Table 8.7. This result supports the observations of Taylor (1973) on five 14-year-old *Eucalyptus grandis* trees sampled in the North-Eastern Transvaal. Taylor concluded that, within each tree, factors other than rate of growth are responsible for differences in wood density.

Table 8.5:- Summary of basic wood density of high- and low-stressed trees (Tabulated density values are averages of five readings)

Height (m)	Stress level	Radius	Basic density ($g.cm^{-3}$)				
			Pith-to-bark position				
			1	2	3	4	5
1,3	Low	1	0,359	0,383	0,434	0,472	0,510
	Low	2	0,350	0,367	0,423	0,482	0,487
	High	1	0,350	0,385	0,478	0,530	0,563
	High	2	0,355	0,371	0,443	0,511	0,577
5,1	Low	1	0,374	0,375	0,399	0,443	0,469
	Low	2	0,367	0,366	0,395	0,439	0,481
	High	1	0,364	0,371	0,443	0,484	0,527
	High	2	0,367	0,374	0,429	0,491	0,547

Table 8.6:- Analysis of variance of density data

A) Breast height

Source of variation	Degrees of freedom	Mean Square	F-ratio
Stress level (S)	1	0,01769	9,59**
Radius (R)	1	0,00003	0,02ns
Radial position (P)	4	0,11010	59,66**
SR	1	0,00000	0,00ns
SP	4	0,00309	1,68ns
RP	4	0,00090	0,49ns
SRP	4	0,00167	0,90ns
Residual	80	0,00185	
Total	99		

B) At 5,1 metre height

Source of variation	Degrees of freedom	Mean Square	F-ratio
Stress level (S)	1	0,02085	22,79**
Radius (R)	1	0,00002	0,02ns
Radial position (P)	4	0,07141	78,04**
SR	1	0,00024	0,26ns
SP	4	0,00412	4,50**
RP	4	0,00045	0,49ns
SRP	4	0,00009	0,10ns
Residual	80	0,00091	
Total	99		

ns = non-significant

** = significant at 1 per cent level

Table 8.7:- Unweighted basic density ($g.cm^{-3}$) of wedges cut from radii one and two, for two heights for high- and low-stressed trees.

Stress level	At breast height		At 5,1 metre height	
	Radius		Radius	
	1	2	1	2
High	0,461	0,461	0,438	0,442
Low	0,435	0,434	0,412	0,410

The relationship between relative distance from the pith and basic density at two heights above ground level in high- and low-stressed trees, are shown graphically in Figure 8.19. At both the sampling heights the mean basic density of low-stressed trees was significantly lower that that of high-stressed trees. Near the pith density differences were small, getting more pronounced towards the stem surface. Although this interaction between stress level and radial position was found statistically significant at only the 5,1m sampling position, there was some suggestion of a similar phenomenon at breast height. This suggests that high-stressed trees are characterised by steeper wood density gradients compared to low-stressed trees, and that the relationship between stress level and basic density cannot be interpreted without reference to the radial position in the tree.

Difference in basic density were quite variable among trees as illustrated by Figure 8.20. These differences were found to be statistically highly significant. In four of the high-stressed trees the pith-to-bark increase in basic density was more rapid, resulting in much higher values at most of the outer sampling positions. One high-stressed tree, however, showed a pattern of increase quite similar to the patterns observed in the five low-stressed trees. This indicates that exceptions do occur in a forest stand, and that tree selection for reduced wood density gradient would not necessarily lead to decreased growth stress levels.

Samples cut from trees sampled for a previous study (see 6.2), provided additional material to verify the relationship found between stress level and basic density. At the same time it provided an opportunity to examine radial density variation in high-and low-stressed trees from a different geographical area using disc samples cut from various other heights above ground level.

Twenty-eight trees were selected for this study, half (14) of which exhibited extremely high amounts of log end-splitting. The rest showed little or no splitting. Wedge samples were cut

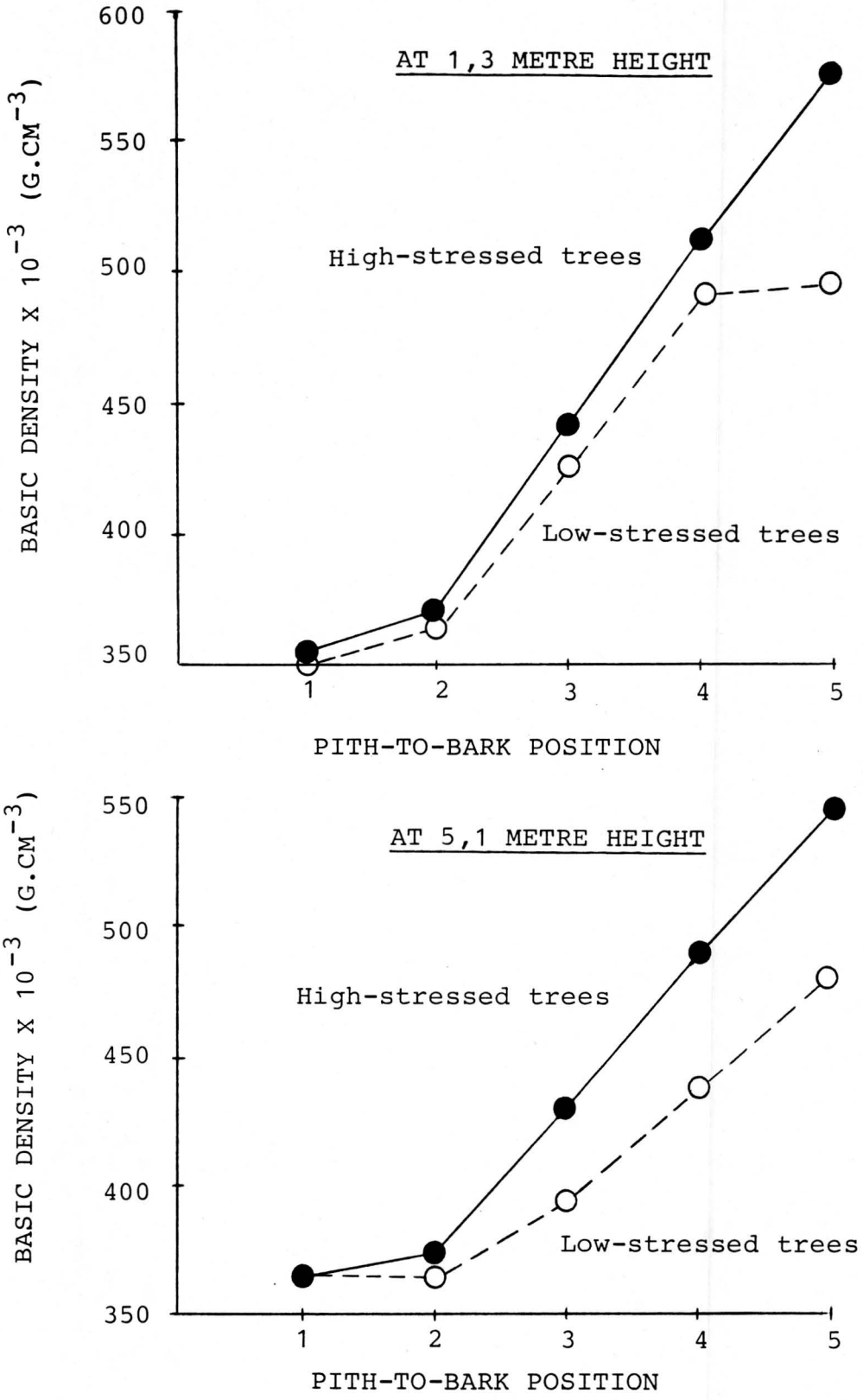


Figure 8.19:- Relationship between basic wood density and relative distance from the pith at two heights in high- and low-stressed trees.

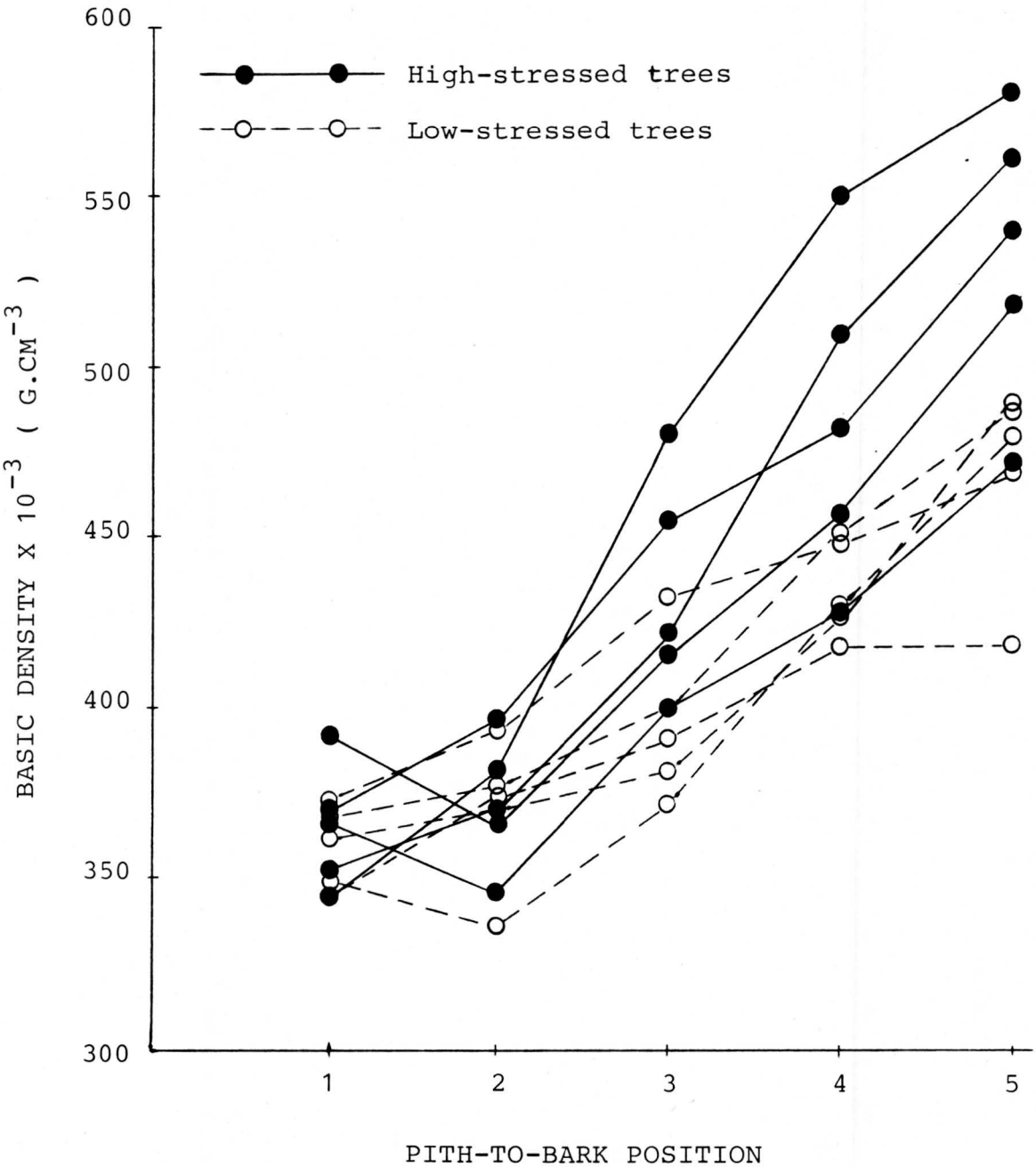


Figure 8.20:- The relationship between relative distance from the pith and basic density at 5,1 metre height for each of the ten tree used in the study.

along a direction perpendicular to the maximum radius to exclude possible tension wood, and divided into segments of equal length for incremental oven-dry density determinations.

The relationships between relative distance from the pith and basic density for high- and low-stressed trees at various heights above ground level, are shown in Figure 8.21. Higher oven-dry densities occurred in the stems of high-stressed trees at 2,4; 4,8 and 7,2 metre heights, supporting the results of the previous investigation, though different heights were involved. An examination of the density distribution patterns on the upper stem indicates no difference between high-and low-stressed trees.

It is also evident from Figure 8.21 that the density differences were less pronounced than those observed between the high- and low-stressed trees of the previous sample (Figure 8.19). This could best be explained by the fact that collapse appeared to be more severe in low- stressed trees (see 8.4.2.3.). Since collapse has an inflating effect on wood density (when the latter is based on oven-dry mass and volume) the density of samples from the low-stressed trees were slightly more inflated in relation to those of high-stressed trees.

8.4.2.3. Collapse

Collapse is the term referring to the unusual shrinkage caused by the caving-in or collapse of the cell walls. This phenomenon occurs during the early stage of drying when the moisture content is well above the fibre saturation point. It is, therefore distinct from "normal" shrinkage because it is not a shrinkage of the walls themselves.

As a result of the abnormal shrinkage caused by collapse,

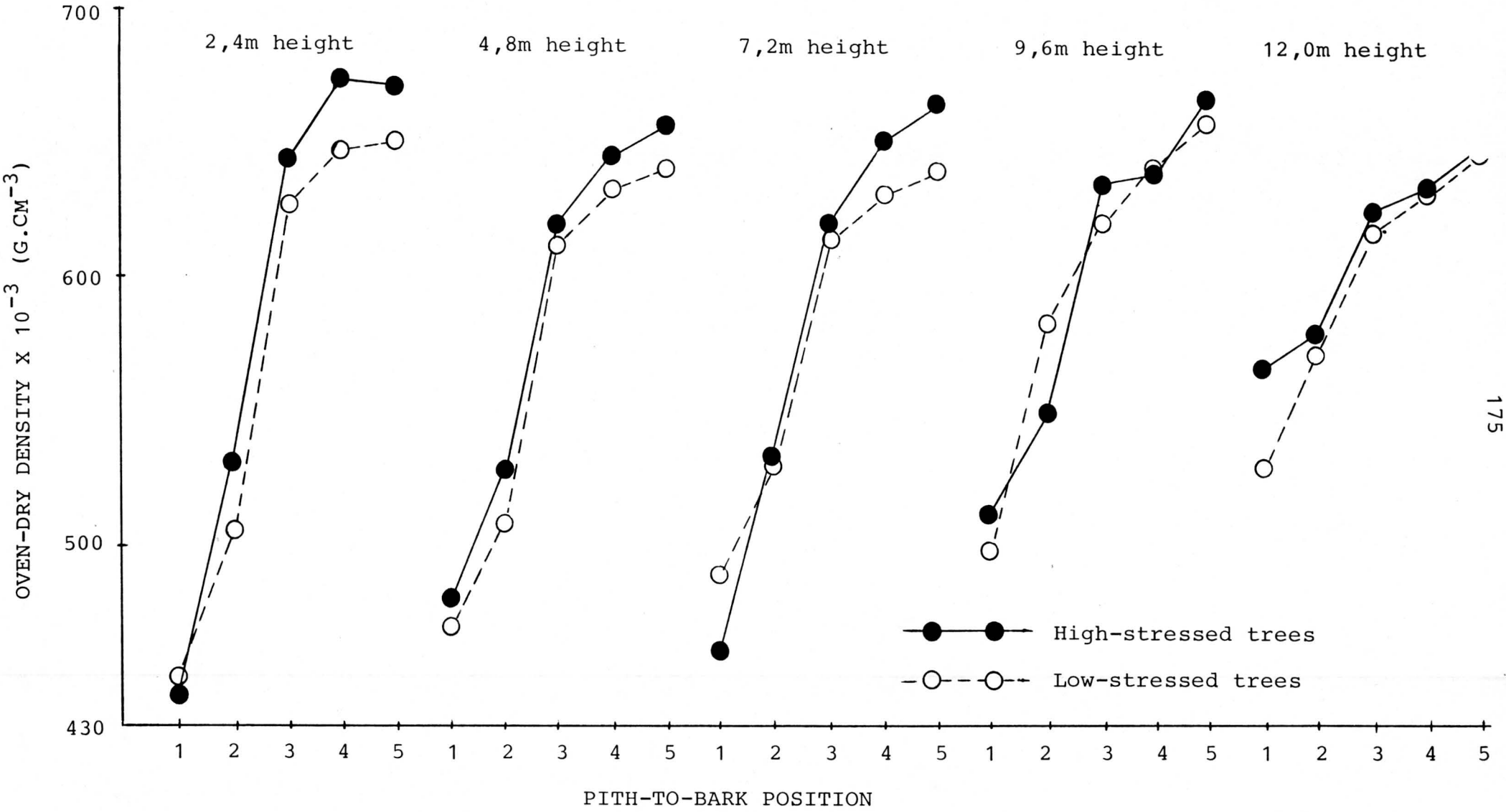


Figure 8.21:- Radial variation in oven-dry wood density for various heights above ground level in low- and high-stressed trees. Data ex Westfalia Estate plantations (comp. M33). Plotted points are averages for 14 trees.

the surface of collapsed wood often appears corrugated or severely deformed. In extreme cases, external as well as internal splits and cracks, may develop. It is frequently accompanied by honeycombing.

A few theories have been proposed to explain the cause of collapse, of which two are widely accepted. The one postulates that collapse is caused by the hydrostatic tension exerted by water in the wet and plastic cell walls, when it is withdrawn from the cell cavities. The other theory attributes collapse to compressive stresses which develop during drying. When these compressive stresses exceed the compressive strength of the wood, the cell walls collapse into the cell cavities (Panshin and de Zeeuw, 1980). Both these conditions occur early in the drying process and may act together to cause collapse (Kauman, 1958).

The degree of collapse seems to be strongly related to the amount of cell wall substance present per unit volume i.e. density. Timber from moist and swampy areas, and fast grown, immature trees, is more prone to collapse than material from other sources (Desch, 1981). Observations in South Africa on *Eucalyptus grandis* wood indicated that collapse increases in severity with a decrease in wood density and (by implication) increase in green moisture content (van Vuuren, N.J.J., S.A. Forestry Research Institute, Personal Communication). Studies carried out on *Eucalyptus regnans and Eucalyptus delegatensis* indicated that the fibre wall to lumen area ratio largely determines collapse intensity. When the 10 percentile value, taken as the value above 90 per cent of the lowest values measured exceeded 5, no collapse occurred during seasoning (Hillis, 1980).

Because of the direct association between stress level and wood density, it was expected that the wood of low-stressed trees will tend to collapse more than the wood of high-stressed trees. To

investigate this, the samples used for density determination were oven-dried and then rated into three collapse classes, i.e. samples showing no or very slight collapse, samples showing a mild amount of collapse, and samples showing severe collapse. Despite the crude manner in which the evaluation was done, the result showed marked differences in the amount of collapse between high- and low-stressed trees (Figures 8.22 and 8.23).

There can be no doubt that the greater amount of thick walled fibres associated high stresses provide more rigidity to the cells to resist the stresses causing collapse in the early stages of drying.

8.4.2.4. Fibre characteristics

There is general agreement among research workers that distance from the pith has a greater effect on fibre length than height in the tree. The radial increase in fibre length is due to the increase in length of the cambial initials with age, combined with enhanced intrusive growth of the cells (Parameswaran and Liese, 1973; Esau, 1965).

Numerous studies on various Eucalypt species and many other genera indicated a rapid increase in fibre length from the pith to the vascular cambium (Bamber and Humphreys, 1963; Taylor, 1973; Higgs, 1969; Hans *et al.*, 1972 and many others. Taylor (1973), working on South African *Eucalyptus grandis*, found this radial variation pattern quite constant for different heights in the tree.

Fibre length seems to vary only slightly with height in the tree. The lack of agreement in literature regarding the type of variation, suggests that this differs between species. Taylor (1973) found no statistical significant difference in fibre length between the different sampling heights for South African *Eucalyptus grandis*. Other studies indicated maximum fibre lengths at 8 metre for *Eucalyptus grandis* (Bamber *et al.*, 1969), at 9 metre for *Eucalyptus pilularis* (Bamber and Curtin, 1974).

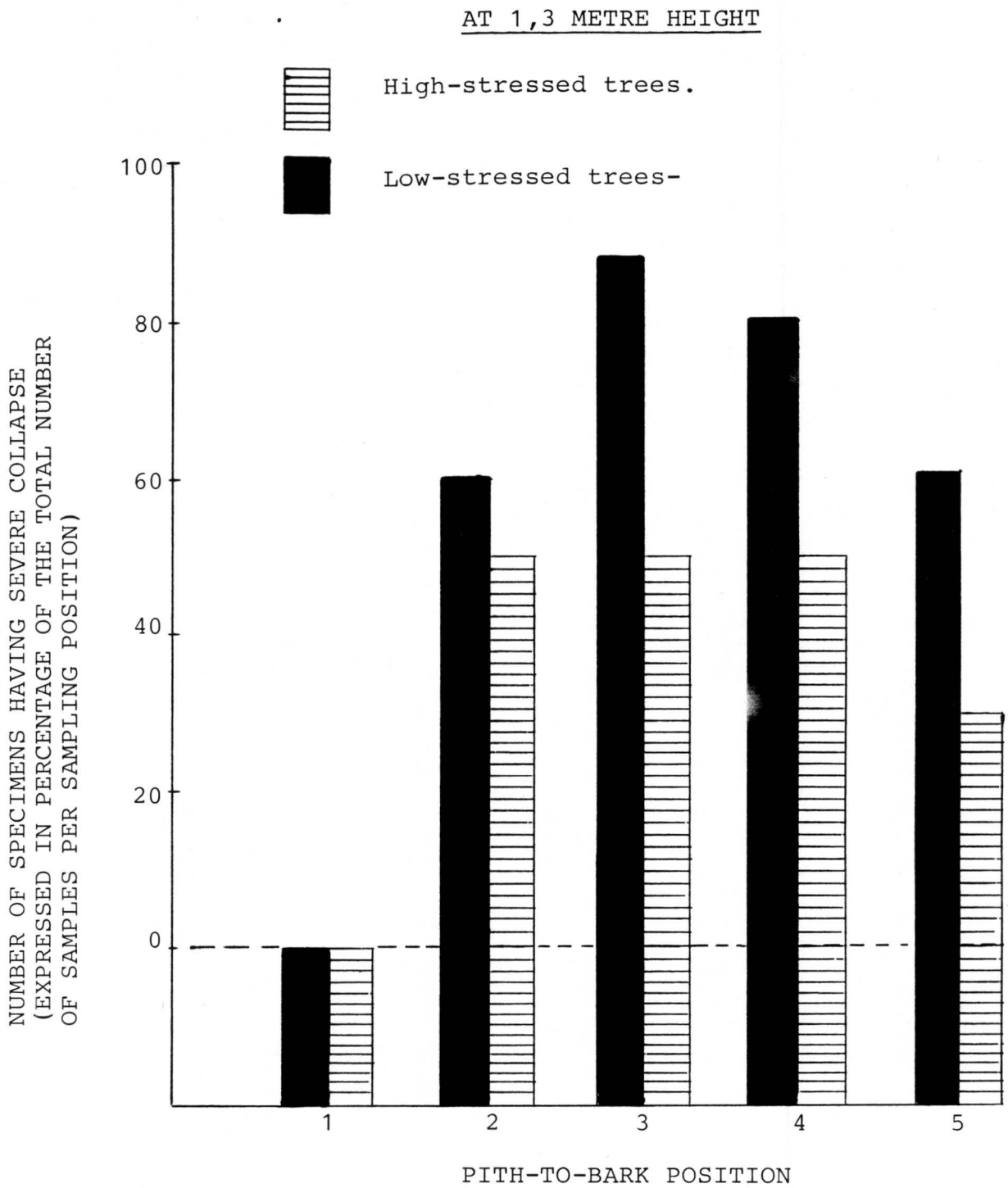


Figure 8.22:- Illustration of the difference in collapse severity between high- and low-stressed trees.

AT 5,1 METRE HEIGHT

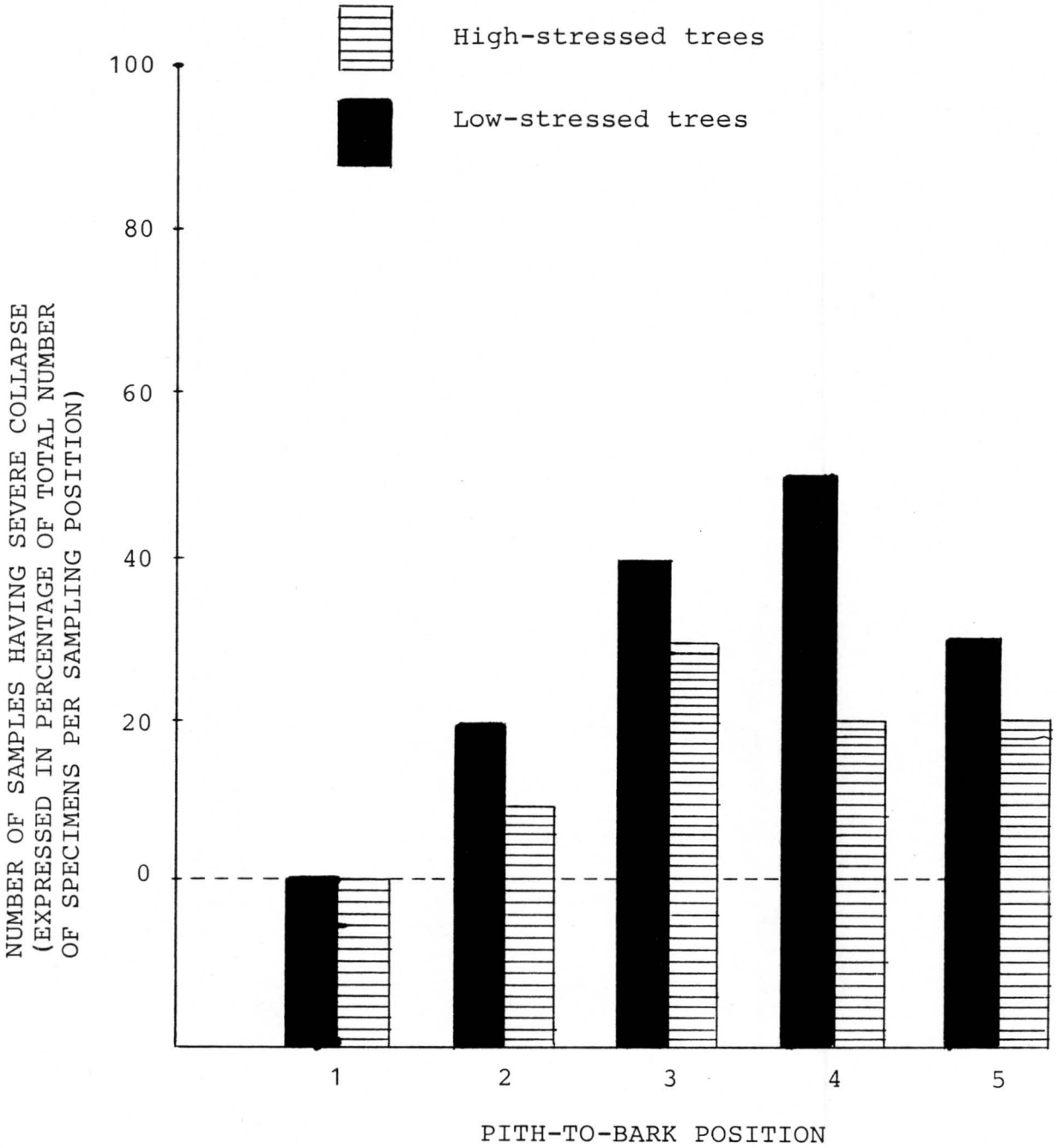


Figure 8.23:- Illustration of the difference in collapse severity between high- and low-stressed trees.

at 17 metre for *Eucalyptus regnans* (Bisset and Dadswell, 1949) at 50 per cent height for *Eucalyptus grandis* (Ranatunga, 1964) and *Eucalyptus gomphocephala* (Stern-Cohen and Fahn, 1964) and at 10 to 50 per cent of the final tree height for *Eucalyptus deglupta* (Davidson, 1972).

Although all trees sampled for this study were straight and vertical, different rates of growth occurred within individual trees, resulting in some degree of pith eccentricity in many of the sample discs prepared.

Not much information on the effect of growth rate on fibre length for Eucalypts is available. In general, rate of growth seems to have no effect on fibre length (Bamber and Humphreys, 1963; Bamber *et al.*, 1982). Hans and co-workers (1972) observed a slight negative effect in *Eucalyptus grandis* grown in Zambia.

When eccentric growth is associated with the formation of tension wood, differences in fibre dimensions do occur when wood of similar age is compared. Chow (1946, 1971) reported that the fibres of the long radius of eccentric Sweetgum and Beech trees are significantly longer than those present in the short radius. Scurfield (1964) found the fibres on the upper side of a bent two and four month old Acacia tree to be either shorter or equal to those from the opposite side. Taylor (1968), on the other hand, found no statistical significant difference between the fibre lengths of the long and short radii of an eccentric Yellow Poplar tree. It is generally agreed that in most hardwood species tension wood fibres tend to be longer and smaller in diameter (Panshin and de Zeeuw, 1980).

In order to establish the importance of the sampling radius, for comparisons of fibre length among trees, a preliminary study was carried out to investigate the effect of radius length. Two trees showing the highest degree of pith eccentricity at both 1,3 and 5,1 metre height, were selected from the sample of 30 trees. The lengths of 90 fibres were measured at five equally spaced

radial positions along and perpendicular to the longest radius. Mean fibre lengths are presented in Table 8.8. Statistical comparisons of these means indicated no significant difference in fibre length between radii at both the sampling heights. The variations from pith to bark were of course highly significant.

It can be concluded from the results of this preliminary analysis that fibre length in *Eucalyptus grandis* is largely governed by the age of the wood, while variations with regard to height in the tree and among cardinal directions, is virtually non-existent. Hence, fibre lengths measured at breast height in any radius may, therefore, be assumed to be a representative for the entire tree. Furthermore, among tree differences in the sample drawn for the between tree study should largely be due to genetic differences, and any association with stress intensity would be of considerable importance to help to explain differences often observed between trees.

An investigation of fibre length variation among high- and low-stressed trees was subsequently performed on the ten trees selected for the study (see 8.4.2.2), using material sampled at breast height perpendicular to the longest radius. Fibres were prepared and measured at five equally spaced positions in accordance with the procedure outlined in section 8.3.4.

More than 4 500 fibre lengths were measured, and statistically analysed. Results of the analysis indicated that the fibres produced by high-stressed trees were significantly longer (at 0,1 probability level) than those of low-stressed trees.

The radial variation patterns of fibre length in high- and low-stressed trees are shown in Figure 8.24. As is apparent from these curves, high-stressed trees in general exhibit a more rapid increase in fibre length with increasing age. This interaction between growth stress and relative distance from the pith was found statistically highly significant (at 0,1 probability level).

Table 8.8:- Mean lengths of fibres in comparable radial positions of two radii at two heights (values are means of at least 90 randomly selected fibres)

Height in Tree (m)	Radius	Fibre length (mm)									
		Tree 1					Tree 2				
		Pith				Bark	Pith				Bark
1,3	Long	0,91	1.06	1,09	1,12	1,12	0,78	1.04	1,11	1,14	1,16
	Short	0,91	0,97	1,08	1,11	1,11	0,77	1,02	1,02	1,14	1,18
5,1	Long	0,86	1,03	1,10	1,16	1,16	0,84	1,01	1,08	1,15	1,15
	Short	0,83	1,04	1,11	1,17	1,19	0,86	0,99	1,09	1,08	1,18

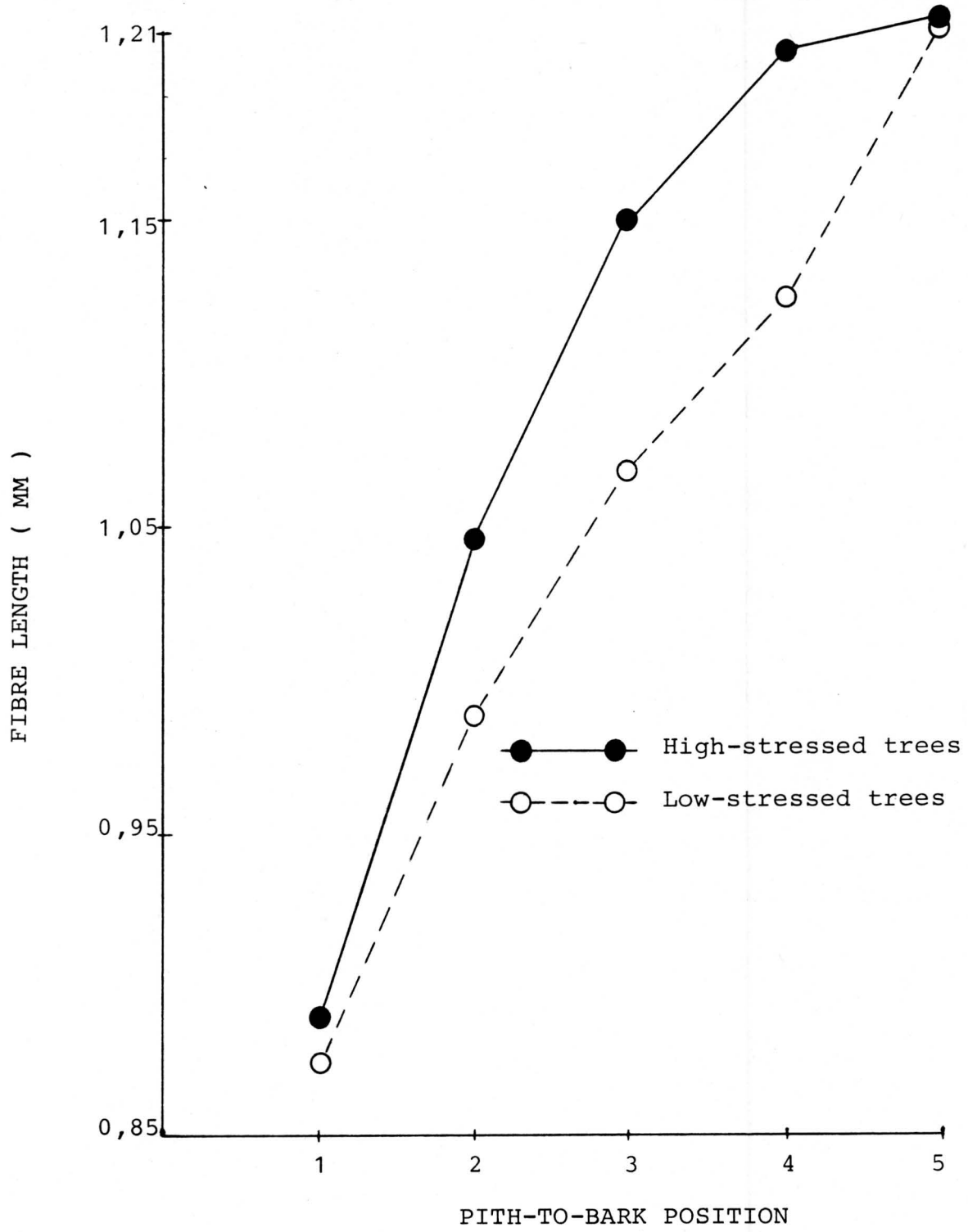


Figure 8.24:- Relationship between relative distance from the pith and fibre length in high- and low-stressed trees. (Plotted points are averages for a minimum of 450 fibres).

Curves, depicting the radial variation in fibre length at breast height for individual trees (Figure 8.25) clearly show differences between the two groups of trees, although some overlapping is apparent, especially in the outer and inner parts of the stem.

Since these trees originated from a similar environment, it can be assumed that a significant proportion of the between-tree variation is attributable to genetic factors. The differences in fibre lengths observed between the two groups of trees suggest that some of the variation is associated with the stress intensity prevailing in the tree.

Fibre diameter increased with distance from the pith (Figure 8.26) which confirms what has been observed in previous studies on South African *Eucalyptus grandis* (Taylor, 1973). The fibre diameters in low-stressed trees were consistently larger at every sampling position compared to those of high-stressed trees, but these differences were small and statistically non-significant. Taylor (1973) also reported between-tree differences in fibre diameter but also found these differences to be statistically insignificant.

Radial variation in lumen diameter was found to be statistically insignificant, but the lumens of fibres of high-stressed trees were on average slightly smaller in diameter compared to those of low-stressed trees. Statistically this difference proved to be significant at the 0,05 level of probability. This difference appeared more pronounced in the outer part of the stem (Figure 8.26).

The double-wall thickness of fibres increased gradually from the pith towards the cambium. The differences between the two groups of trees were small and statistically non-significant in the central parts of the stem, but in the outer parts of the stem the fibre walls were significantly thicker in the high-stressed trees (Figure 8.26).

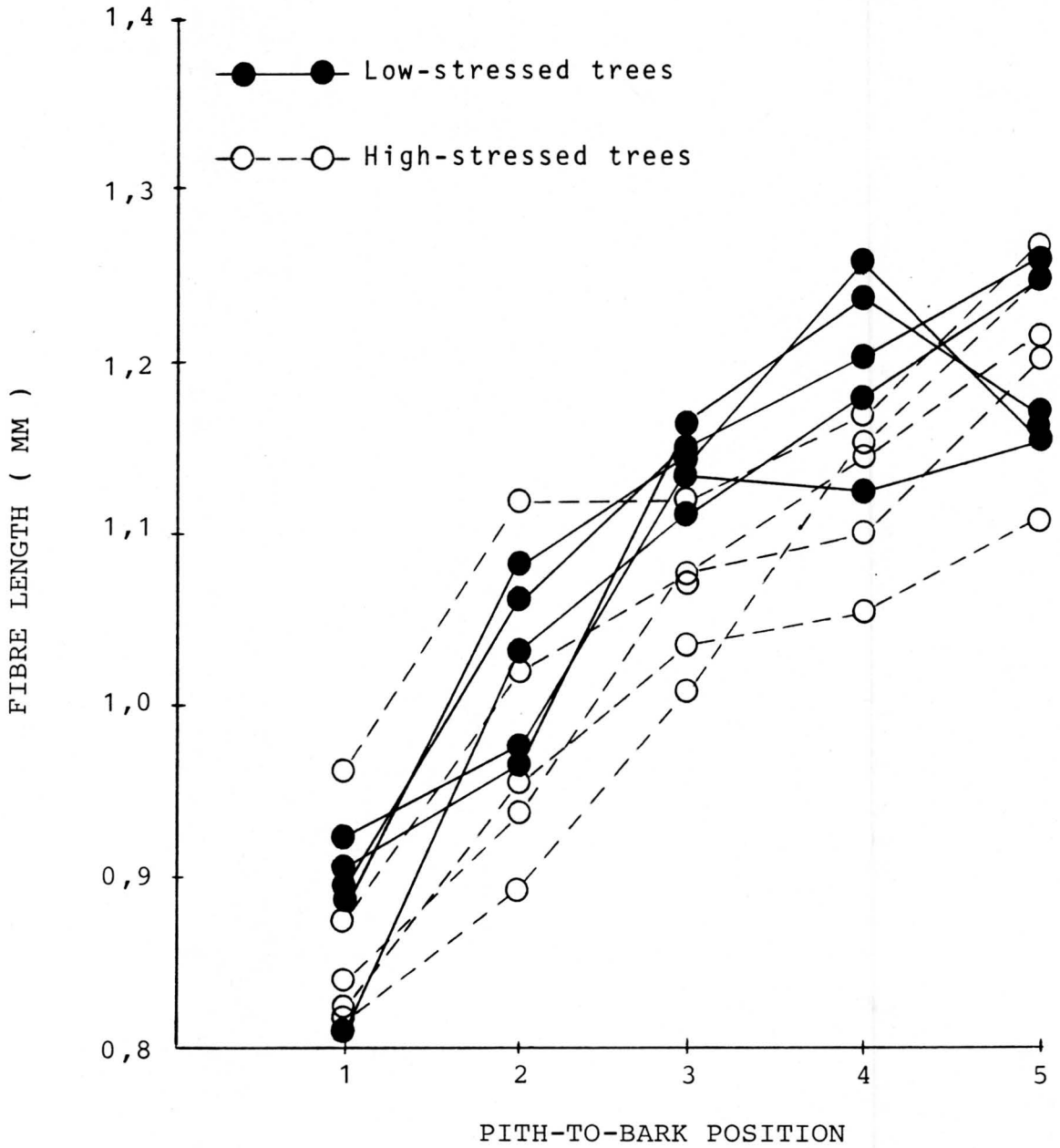


Figure 8.25:- Radial variation in fibre length in individual trees used in the study. (Each data point is the average of a minimum of 90 measurements.)

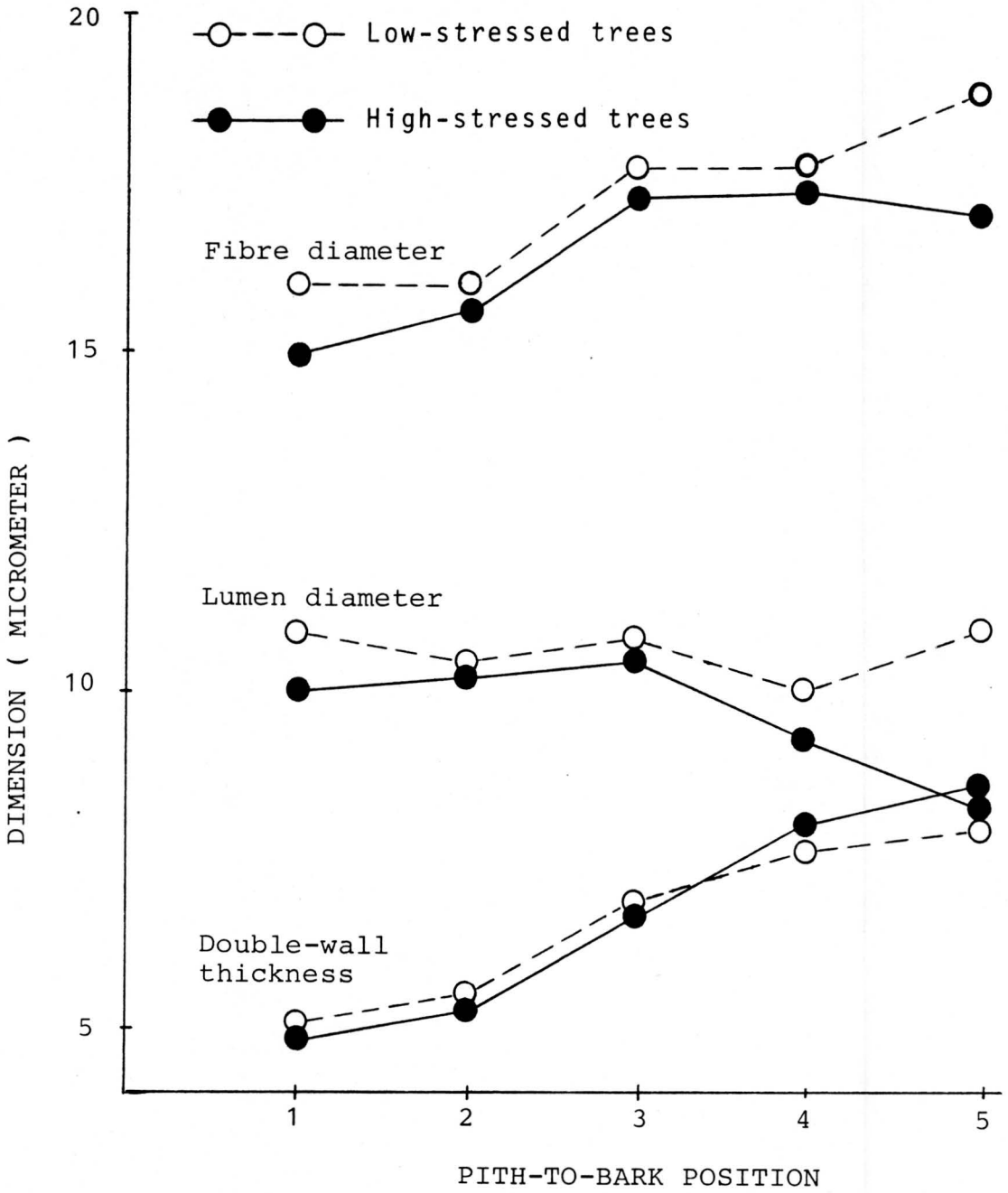


Figure 8.26:- Radial variation in fibre diameter, lumen diameter and double-wall thickness in high- and low-stressed trees.

This indicates that increased fibre cell diameter is not necessarily associated with an increased proportion of cell wall substance. Fibre cells of low-stressed trees, although larger in diameter, contained proportionally less cell wall substance than fibres in high-stressed trees. Although no difference in fractional wall volume of fibres was noticed in the central parts of the stem, marked differences occurred in the outer parts of the stem (Figure 8.27). Since fractional wall volume of fibres is closely associated with basic density (Figure 8.28), it can be concluded that the observed differences in fractional wall volume largely account for the differences in basic density found in the outer stem regions between high- and low-stressed trees.

Differences in the cross-sectional fibre dimensions observed both radially and between the two groups of trees examined, resulted in important differences with regard to some of the other fibre characteristics (Table 8.9).

The ratio of fibre length to fibre diameter increased gradually from the pith to the bark. This indicates that the increase in fibre length is not associated with proportional increase in fibre diameter. In other words, fibres near the pith possess proportionally a larger diameter than those formed in the outer parts of the stem. This ratio was found significantly higher in high-stressed trees at all radial sampling positions. Although the relationship between this ratio and the strength properties of paper apparantly varies between species, it can be expected that the properties of paper produced from fibres originating from high-stressed trees will be different as regards certain strength properties, and properties such as ease of sheet formation, sheet smoothness and opacity (Davidson, 1972).

The ratio of lumen diameter to fibre diameter decreased gradually with distance from the pith. Since basic density increased radially from the pith, a corresponding decrease in the relative proportion of void in the cross-section was of course expected. Differences between the two groups of trees studied only occurred in the outer parts of the stem.

Table 8.9:- Radial variation in fibre properties in high- and low-stressed trees

Fibre property	Stress level	Pith-to-bark position 1	2	3	4	5
Felting coefficient (FL/D)	Low	55	62	61	65	65
	High	60	67	67	70	72
Flexibility coefficient (L/D)	Low	0,68	0,65	0,61	0,59	0,58
	High	0,68	0,66	0,60	0,54	0,49
Runkel ratio (2W/L)	Low	0,48	0,54	0,65	0,76	0,71
	High	0,49	0,52	0,65	0,89	1,05
Fibre density (2W/D)	Low	0,32	0,35	0,39	0,43	0,42
	High	0,32	0,34	0,40	0,46	0,51
Fibres mm^{-2}	Low	4675	4740	3860	3820	3380
	High	5280	4920	3920	3900	4100
Fractional wall volume (per cent)	Low	54	57	63	68	66
	High	54	57	63	71	76
Fractional lumen volume (per cent)	Low	46	41	37	32	33
	High	46	41	37	29	24

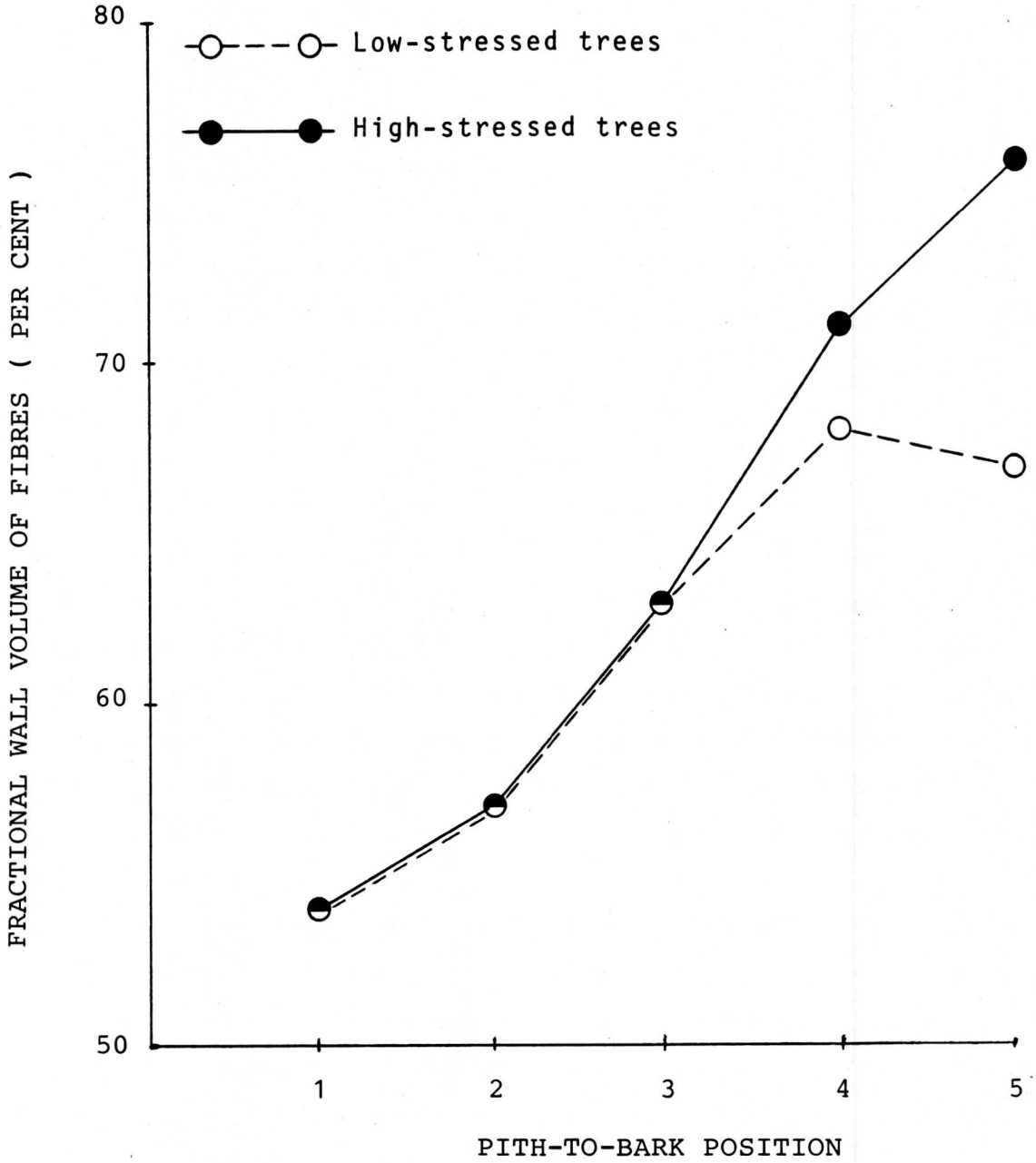


Figure 8.27:- Radial variation in fractional fibre wall volume in high- and low-stressed trees.

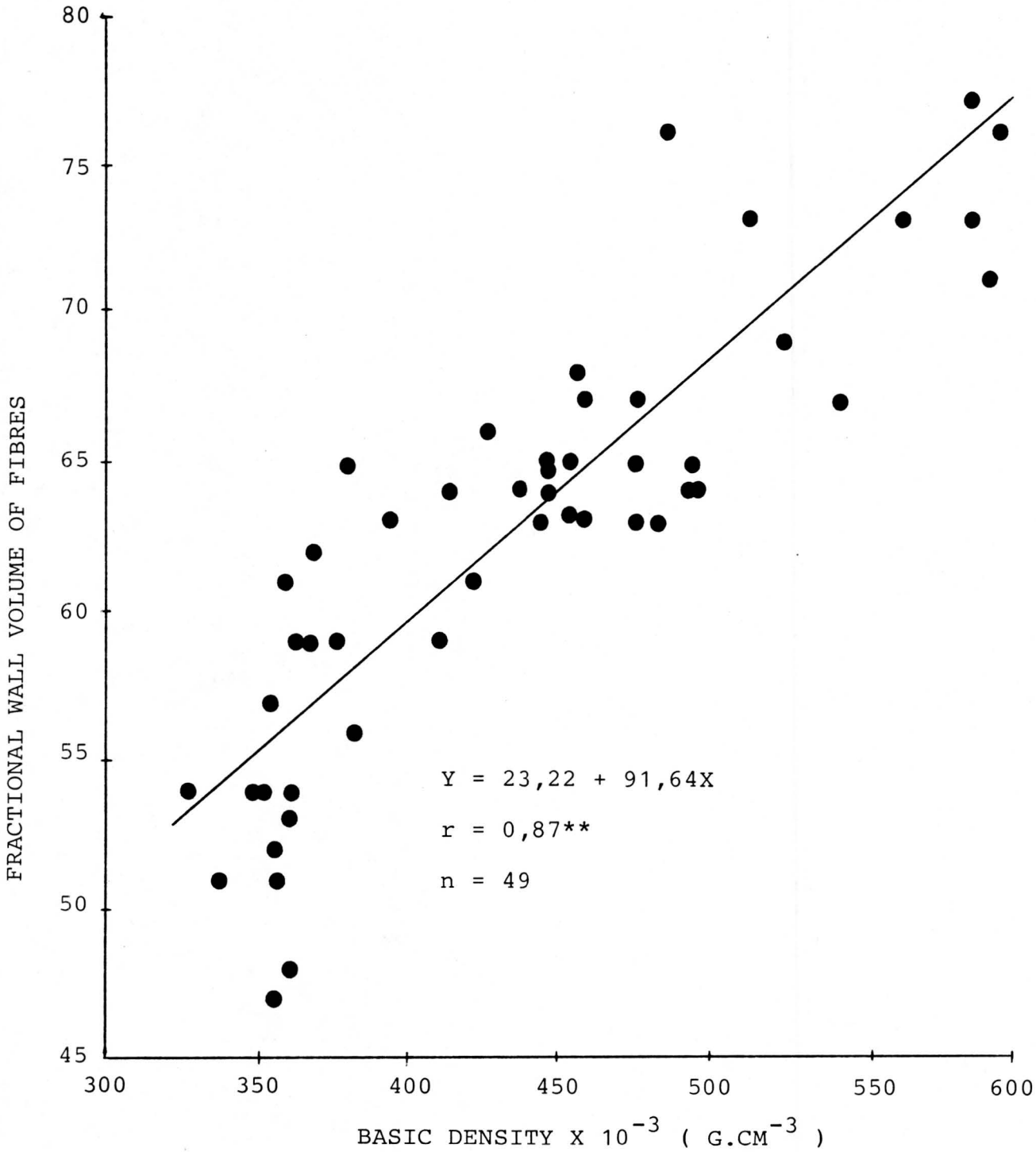


Figure 8.28:- Relationship between fractional wall volume of fibres and basic density.

The ratio of double-wall thickness to fibre diameter expresses the relative proportion of wall substance in fibre cross-section. This ratio increased from the pith towards the bark, and, since it correlates well with wood density, corresponding differences occurred between the two groups of trees studied.

8.4.2.5. Vessel characteristics

The tangential diameter of vessels and number of vessels per square millimeter were measured at breast height at five equally spaced radial positions (see 8.3.4.2).

In general, tangential diameter of vessel cells increased with increasing radial distance from the pith, while vessel number per unit area simultaneously decreased (Figure 8.29). Similar variations have been reported by Taylor (1973) and Bamber *et al.* (1963) in *Eucalyptus grandis*, Davidson (1972) and Dadswell (1958) in *Eucalyptus regnans*, Bamber and Curtin (1974) in *Eucalyptus pilularis*, Chudnoff and Tischler (1963) in *Eucalyptus camaldulensis*, Nicholls and Phillips (1970) in *Eucalyptus viminalis*, Nguyen (1977) in *Eucalyptus dalrympleana*, and many other genera (Aung, 1962; Taylor and Wooten, 1973).

Statistical analysis of the 4 500 vessel diameters measured revealed a highly significant difference between high- and low-stressed trees (at 0,01 level of significance). In general high-stressed trees seemed to possess vessels of a larger diameter, being more pronounced in the central regions of stem (Figure 8.29). Vessel frequency was found slightly but significantly higher at all radial sampling positions (Figure 8,29). Since the percentage is determined by both vessel size and frequency, these differences will have an important effect on the volumetric composition of trees of different stress intensity.

Differences in vessel diameter as well as vessel frequency were statistically significant (Table 8.10) and confirmed results previously obtained for *Eucalyptus grandis* (Taylor 1973). Since there were no apparent environmental factors to account for these differences, a large part of the observed variations must be attributable to genetic factors.

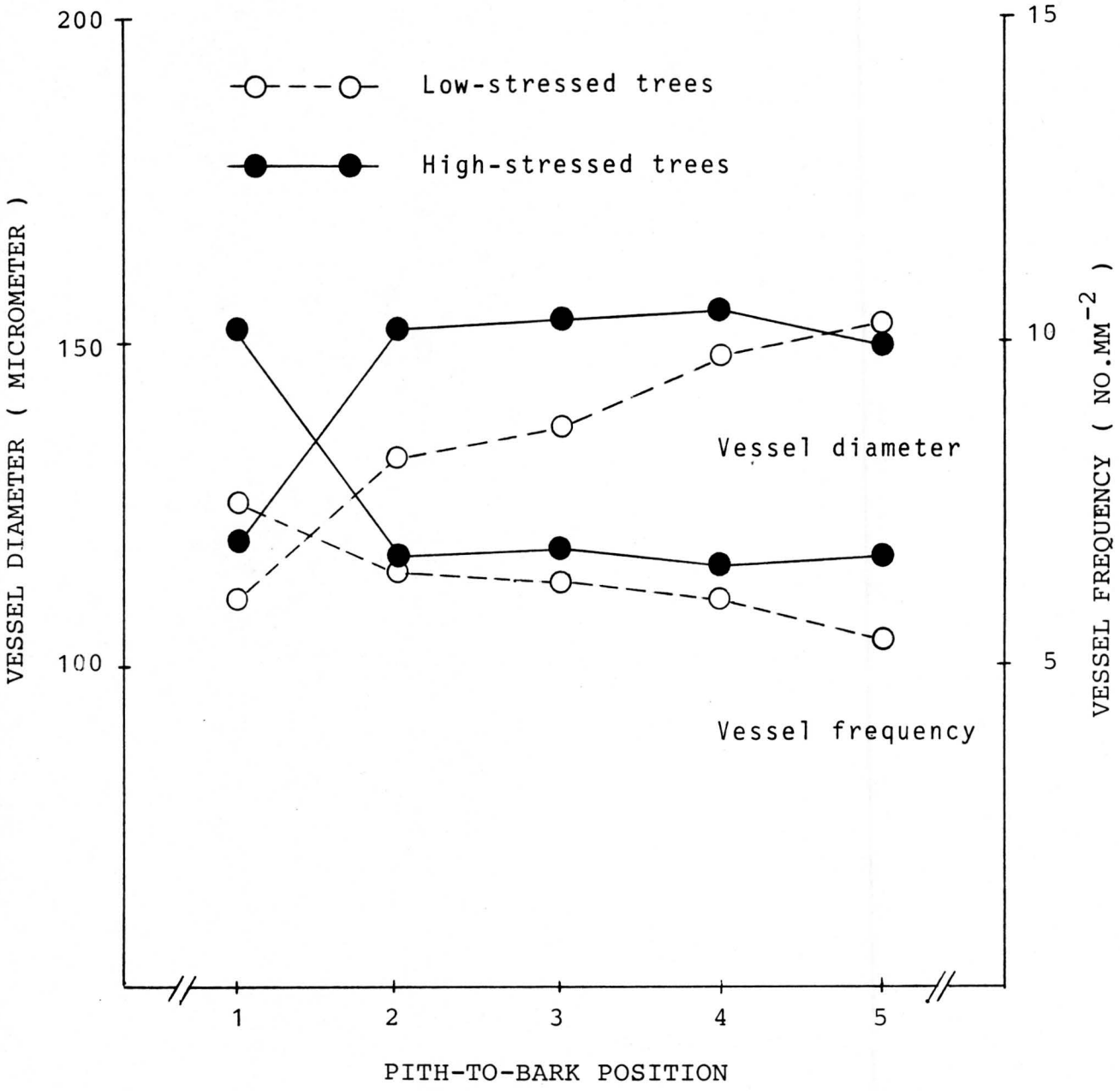


Figure 8.29:- Relationship between relative distance from the pith, and vessel size and frequency in high- and low-stressed trees

Table 8.10:- Tangential diameter (in millimeter) of vessels at different distances from the pith of each sample tree. Number of vessels per square millimeter (vessel frequency) appear in parenthesis.

Stress level	Tree no.	Vessel Diameter and Vessel Frequency				
		Pith-to-bark position				
		1	2	3	4	5
Low	1	missing	130(5.3)	126(7.0)	153(6.7)	153(5.6)
	2	103(8.1)	134(7.3)	147(6.7)	147(6.4)	147(5.6)
	3	109(8.8)	127(7.5)	130(6.0)	147(5.6)	172(5.1)
	4	138(8.0)	144(6.7)	155(5.9)	152(6.8)	156(6.0)
	5	129(5.2)	130(6.1)	126(6.0)	146(4.8)	162(5.0)
Mean		110(7.5)	131(6.6)	136(6.3)	149(6.1)	153(5.2)
Standard dev.		21	22	25	26	27
High	1	125(9.8)	148(7.0)	163(6.4)	147(6.2)	146(5.0)
	2	122(10.4)	161(6.7)	143(6.7)	142(7.6)	142(8.4)
	3	104(9.4)	130(7.8)	147(8.9)	151(7.8)	162(8.7)
	4	96(9.4)	154(4.9)	159(6.6)	166(5.7)	151(6.0)
	5	121(8.6)	141(6.6)	158(5.5)	169(5.6)	182(5.8)
Mean		119(10.3)	151(6.6)	153(6.8)	155(6.6)	150(6.3)
Standard dev.		21	23	24	23	30

8.4.2.6. Ray characteristics

Statistical analysis of 4 500 ray widths measured at various distances from the pith indicated highly significant differences between low- and high-stressed trees (0,01 level of significance). Considerable variation occurred between trees and no direct association with degree of log end-splitting (stress level) was evident (Table 8.11). However, average values for ray width were consistently higher in low-stressed trees at all sampling positions (Figure 8.30). In both groups of trees ray widths increased with age, reaching more or less constant values towards the outer parts of the stem.

Ray frequency (expressed as the number of rays crossing a tangential line of unit length) was found as variable within an individual tree as it is among trees. In most trees ray density decreased towards the pith. At radial positions 2 and 3 differences were particularly pronounced with ray frequency being almost consistently higher in all low-stressed trees (Figure 8.31).

Since ray volume is contingent upon their size and their frequency, the lower values observed in high-stressed trees may account to a lesser extent for the higher wood density recorded.

It can, therefore, be concluded from these results that an increase in level of growth stress appears to be associated with a decrease in ray width and perhaps also in ray frequency. It must be emphasized that the association seems to be weak and also of little practical importance.

8.4.2.7. Volumetric composition

Variation in cell size, frequency and wall thickness of the various tissue types, and the volume they occupy in wood, may have an important effect on wood properties, especially wood density.

Table 8.11:- Widths of rays at different distances from the pith of each sample tree (number of rays per millimeter appear in parenthesis).

Stress group	Tree number	Ray width (micrometer)					Average	Average Tree Splitting (Score)
		Relative distance from Pith						
		1	2	3	4	5		
Low	1	Missing	15,5(15,2)	16,9(12,2)	15,0(9,4)	16,0(9,3)	15,9(11,5)	1,4
	2	18,3(10,1)	18,0(9,4)	17,4(11,1)	19,4(10,1)	23,2(9,4)	19,3(10,0)	1,4
	3	16,3(13,5)	18,6(12,2)	19,9(12,2)	18,9(10,1)	16,6(9,4)	17,9(11,5)	2,4
	4	13,5(8,7)	14,5(10,4)	17,5(10,1)	19,5(12,2)	20,1(8,7)	17,0(10,0)	2,8
	5	22,0(10,1)	18,1(11,1)	21,5(10,1)	22,8(10,1)	18,7(11,1)	20,6(10,5)	1,8
$\bar{X}$		17,5(10,6)	16,9(11,7)	18,4(11,1)	19,1(10,4)	18,9(9,6)		
s		5,3(2,0)	4,9(2,2)	4,8(1,1)	6,6(1,1)	6,7(0,9)		
High	1	12,8(12,2)	13,6(10,1)	15,5(9,6)	14,9(9,4)	14,9(10,1)	14,3(10,3)	13,8
	2	17,1(12,2)	19,1(9,4)	17,1(10,1)	19,9(12,2)	18,3(12,2)	18,3(11,2)	5,3
	3	14,1(9,9)	15,4(7,6)	13,2(8,1)	17,6(8,7)	13,3(8,7)	14,7(8,6)	6,3
	4	14,8(10,1)	15,6(9,7)	18,2(7,2)	19,0(9,6)	24,0(9,7)	18,3(9,3)	6,7
	5	14,0(11,1)	13,7(8,7)	14,1(6,9)	14,0(9,4)	13,0(8,1)	13,8(8,8)	6,2
$\bar{X}$		14,6(11,1)	15,5(9,1)	15,6(8,4)	17,1(9,9)	16,7(9,8)		
s		4,2(1,1)	4,5(1,0)	4,4(1,4)	5,2(1,4)	6,7(1,6)		

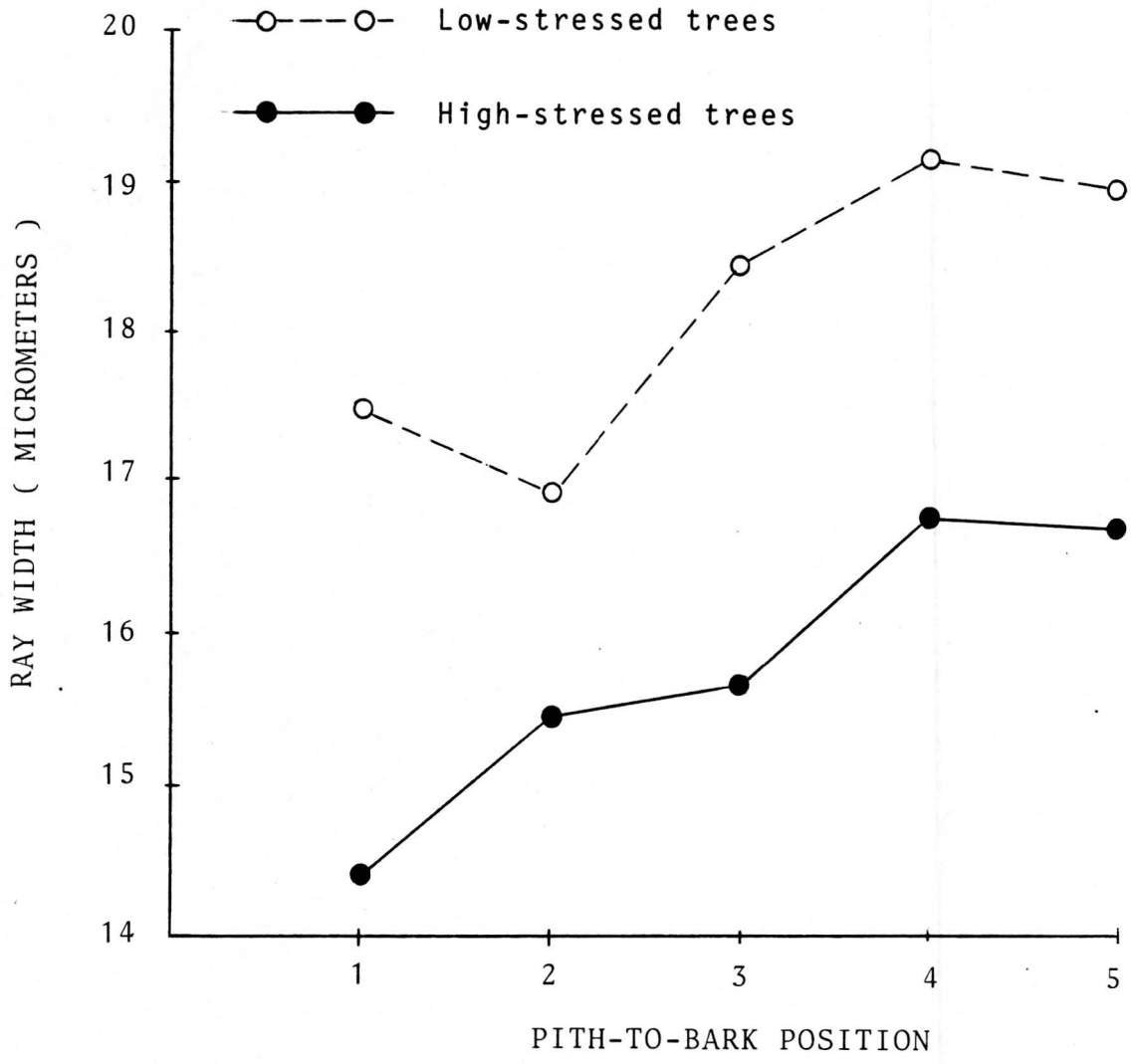


Figure 8.30:- Variation in ray width with relative distance from the pith in high- and low-stressed trees. (Each data point represents an average of 450 measurements.)

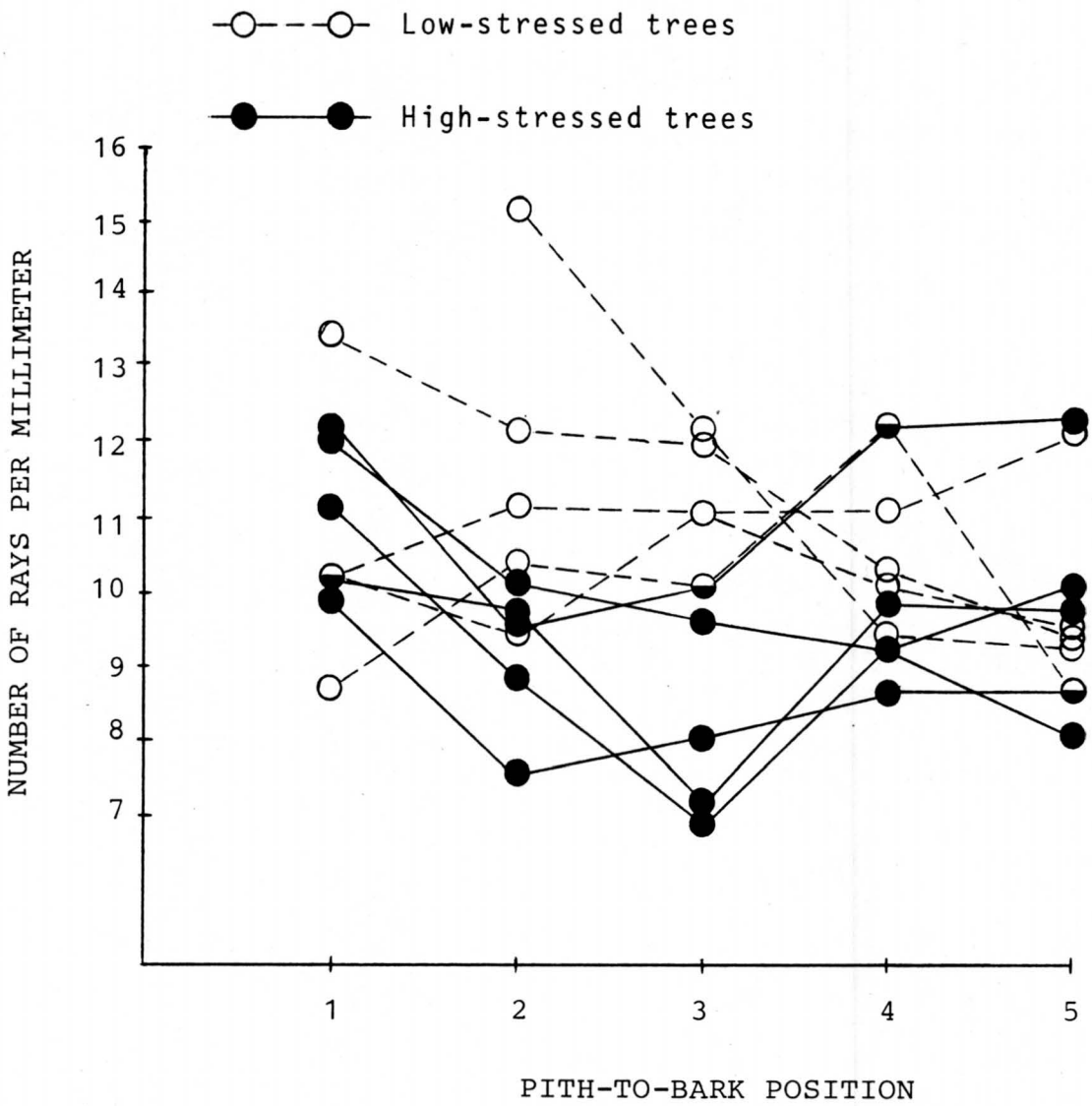


Figure 8.31:- Variation in ray frequency with relative distance from the pith. (Each data point represents an average of counts taken at about ten sampling positions in the tangential section.)

The proportionate volume of vessels, rays and fibres showed large variations within as well as between trees. The average volumes of the various tissue types recorded in this study for high- and low-stressed trees are shown in Figure 8.32.

Vessel volume remained more or less the same with increasing distance from the pith. However, the proportion of wood occupied by vessels was consistently and significantly higher in high-stressed trees, but the differences were small.

As regards ray volume, no relationship seemed to exist with distance from the pith. However, wood of high-stressed trees contained significantly less ray tissue at all radial sampling points.

Both vessel and ray tissue are thin walled and consequently have a major effect in determining the void volume present in wood. An increase in the proportion of these tissue types must obviously be associated with a decrease in the total amount of fibres and axial parenchyma.

In low-stressed trees the total volume of fibres and axial parenchyma showed little variation with increasing distance from the pith. In high-stressed trees the radial variation appeared somewhat more variable. Slightly higher volumes occurred in the central parts of the radius. These differences were statistically significant.

8.4.2.8. Discriminant Analysis

The purpose of this analysis was to develop discriminant functions based on various anatomical properties and basic density, and to test the effectiveness of these functions in discriminating high-stressed from low-stressed trees.

On an average, differences between high- and low-stressed trees have been found for many of the variables considered, as shown by

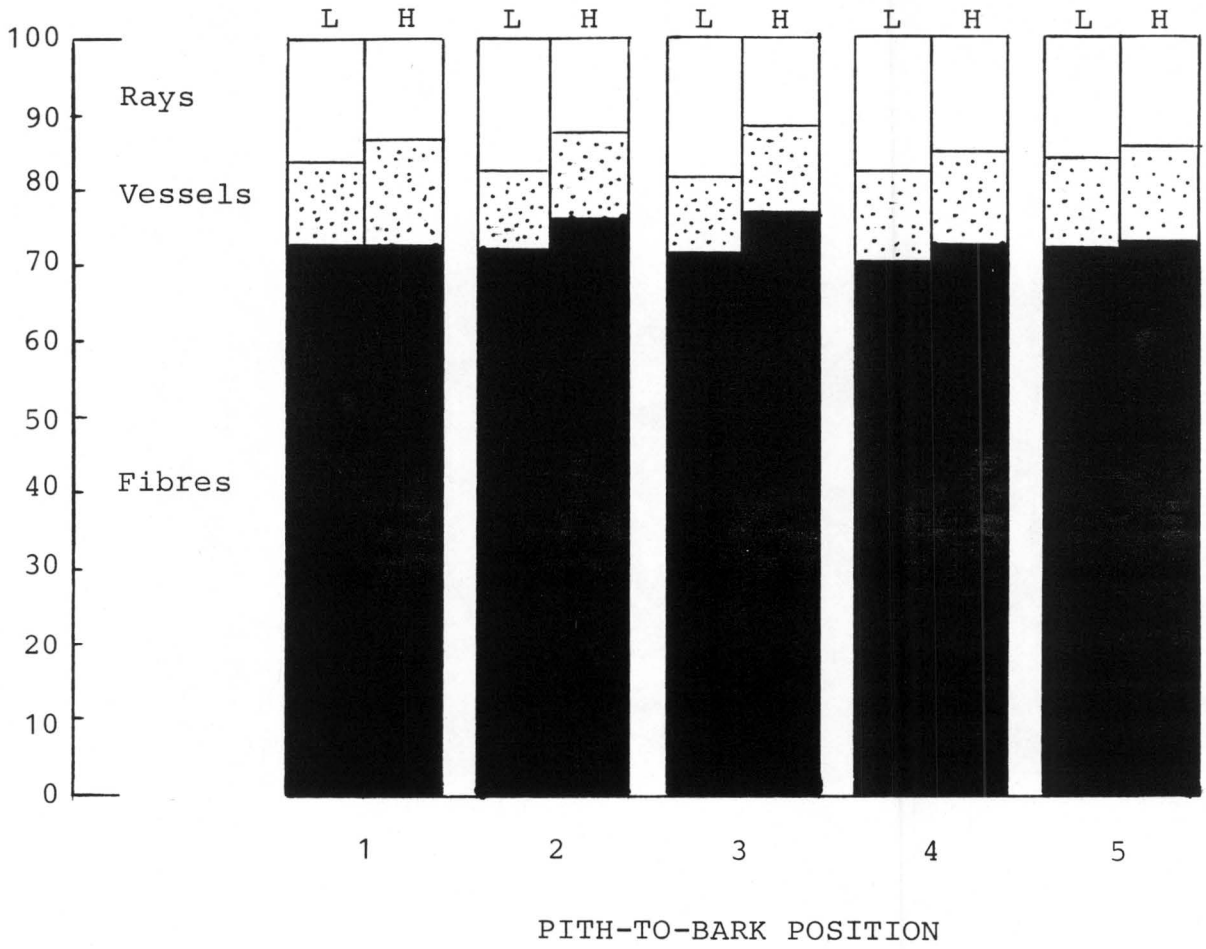


Figure 8.32:- Relationship between the distance from the pith and the proportion of rays, vessels and fibres in the wood of high-stressed (H) and low-stressed (L) trees. (Fibre volume includes axial parenchyma.)

the contrast of mean values (Table 8.12). Although these figures suggest that high-stressed trees can be distinguished from low-stressed trees in gross terms, considerable overlap occurred between trees. As a consequence, mean anatomical and density values are insufficient to distinguish between trees containing widely different levels of growth stress.

The variables listed in Table 8.12 were used in a series of stepwise discriminant analyses in order to fit a linear function of the form:

$$Z = B_o + B_1X_1 + B_2X_2 + \ldots\ldots B_kX_k$$

where: B_1, B_2 .... B_k are weighting coefficients assigned to the measured variables X_1, X_2, ... K_k. Weighting coefficients are assigned such that the ratio of the square of the difference between the means of the groups to the sum of squares within groups are maximised.

Selection of variables were done in a forward manner, in other words, at each step the variable that adds the most to the separation of the groups is entered into the discriminant function. Classification of an individual was determined by the Mahalanobis D^2 and from the posterior probability for each group.

To determine which radial position in the tree would provide the best basis for discriminating between trees of different stress intensities, a series of analyses were conducted for each of the radial positions. It was invisaged that these analyses would provide information regarding the possibility to discriminate between high- and low-stressed trees at the various stages in the life of the tree.

Table 8.12:- Mean values of various anatomical features for trees of different growth stress intensities.

Wood Property	All Data	Low-stressed Trees						High-stressed Trees					
		All Data	Pith-to-bark position 1	2	3	4	5	All Data	Pith-to-bark position 1	2	3	4	5
Vessel volume (%)	11,7	11,0	10,5	10,8	10,3	11,7	11,8	12,3	13,4	11,6	11,6	12,0	12,9
Ray volume (%)	15,3	17,3	16,8	17,5	18,4	17,7	16,0	13,4	13,9	12,4	11,5	15,0	14,4
Fibre volume (%)	73,0	71,8	72,8	72,0	71,3	70,7	72,2	74,3	72,7	75,9	76,9	73,0	72,7
Vessel diameter (μ)	141,1	138,4	119,8	133,0	136,8	140,8	158,0	143,6	113,6	146,8	154,0	147,2	156,6
Vessel frequency	6,8	6,3	7,5	6,6	6,3	6,1	5,5	7,3	9,5	6,6	6,8	6,6	6,8
Ray width (μ)	17,0	18,2	17,5	16,7	18,4	19,1	18,9	15,9	14,6	15,5	15,6	17,1	16,7
Rays per mm	10,1	10,7	10,6	11,7	11,1	10,4	9,6	9,6	11,1	9,1	8,3	9,9	9,8
Fibre length (mm)	1,08	1,06	,87	,99	1,07	1,12	1,20	1,09	,88	1,03	1,15	1,20	1,20
Fibre diameter (μ)	16,7	17,1	15,9	15,9	17,6	17,5	18,6	16,3	14,8	15,4	17,2	17,2	16,9
Fibre lumen diameter (μ)	10,1	10,5	10,8	10,4	10,7	9,9	10,9	9,6	10,0	10,2	10,4	9,3	8,2
Double-wall thickness (μ)	6,6	6,6	5,1	5,5	6,7	7,6	7,7	6,7	4,8	5,3	6,8	8,0	8,6
Felting coefficient	64,6	62,0	55,1	62,4	61,3	64,7	65,4	67,1	59,9	66,8	67,1	70,0	71,5
Flexibility coefficient	,60	,62	,68	,65	,61	,59	,58	,59	,68	,66	,60	,54	,49
Runkel ratio	,68	,63	,48	,54	,65	,76	,71	,71	,48	,52	,65	,89	1,05
Fractional wall-volume	63,1	61,9	54,0	57,4	63,2	67,6	65,8	64,2	54,4	56,8	63,4	70.8	75,8
Wood Density ($g.cm^{-3} \times 10^{-3}$)	436	420	357	368	411	472	480	451	355	371	442	511	577

A "Jackknife" validation procedure was employed to reduce the bias on the group classification. This involves the testing and classifying of each sample using a function built upon the rest of the observations (Table 8.13).

Basic wood density in the sapwood zone (position 5) of the tree was the most effective variable for discrimination and led to the correct classification of all trees. The addition of the ratio of lumen to fibre diameter to the model was significant, but did not lead to an improvement in the discriminant functions.

At 80 per cent distance from the pith (position 4), fibre length emerged as the most effective variable for discrimination. The addition of fibre volume to the model was significant and led to the successful classification of 90 per cent of the trees.

At positions 2 and 3, ray volume was found to be the best variable for discrimination, leading to the correct classification of 70 and 90 per cent of the tree respectively. At about 10 per cent distance from the pith, 7 out of 9 trees were correctly classified using vessel frequency as discriminating variable.

By pooling the data, ray volume was again found the best variable for discrimination. The addition of lumen diameter to the model was significant but did not improve the effectiveness of the discriminant function. Quite a number of the samples were misclassified, but most of them originated from two trees only.

The best equations for each sampling portion for discriminating among the two stress groups are given in Table 8.14. The canonical variable scores for each observation are plotted in Figure 8.33.

It is evident that the discriminant functions developed, increased in their efficiency with increasing distance from the pith. This suggests that the ease of separating high- and

Table 8.13:- Order of entry of significant variables and the percentage of trees classified correctly after the "Jackknife" procedure has been employed

Variable	Correct classifications (per cent)											
	All positions		Pith-to-bark position									
			1		2		3		4		5	
	L[1]	H[2]	L	H	L	H	L	H	L	H	L	H
Wood density	*	*	*	*	*	*	*	*	*	*	100	100
Ray volume	75	76	*	*	60	80	100	80	*	*	*	*
Vessel frequency	*	*	75	80	*	*	*	*	*	*	*	*
Lumen diameter	79	68	*	*	*	*	*	*	*	*	*	*
Fibre length	*	*	*	*	*	*	*	*	80	80	*	*
Flexibility coefficient	*	*	*	*	*	*	*	*	*	*	100	100
Fibre volume	*	*	*	*	*	*	*	*	80	100	*	*

L Low-stressed trees
H High-stressed trees
* These, as well as those variables not included in the table, were non-significant at the 0,05 level of significance.

Table 8.14:- Equations of anatomical variables used to discriminate among trees of different growth stress intensities.

Pith-to-bark position	Equation	Canonical correlation
5	Z = 10,27 - 48,21Density + 28,36 Flexibility coefficient	0,97
4	Z = 48,83 - 0,30Fibre volume - 0,02Fibre length	0,82
3	Z = - 6,29 + 0,42Ray volume	0,85
2	Z = - 5,14 + 0,34Ray volume	0,70
1	Z = 7,69 - 0,89Vessel frequency	0,71
All positions	Z = - 9,47 + 0,27Ray volume + 0,53Fibre lumen diameter	0,62

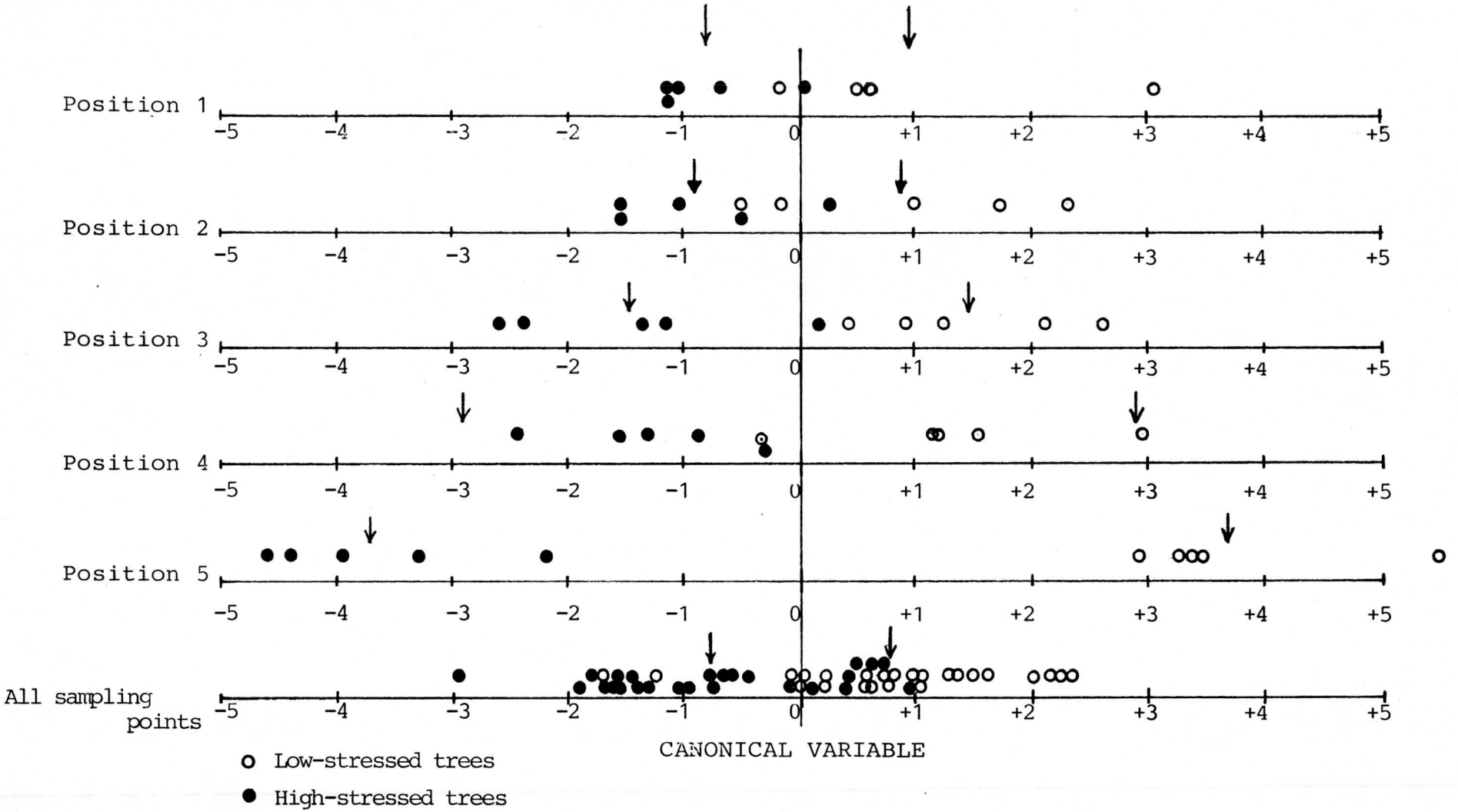


Figure 8.33:- Anatomical properties of high- and low-stressed trees as classified by the discriminant functions using the best equations for discriminating among the two stress groups (Arrows indicate mean coordinates)

on the basis of their anatomical properties, will increase with increasing age. Although the discriminant functions obtained for positions close to the pith were low in efficiency, separation of high- and low-stressed trees at an early stage in their life nevertheless seems possible.

8.5 Discussion

In specimens taken from two leaning *Eucalyptus grandis* trees, an association was found between longitudinal growth strain measured at the periphery of the stem, and several properties of the wood.

In both trees fractional wall volume of fibres increased with increasing growth strain. However, no relationship could be found between stress intensity and basic wood density in spite of the good relationship that normally exists between fractional wall volume of fibres and basic wood density. Vessel volume increased with increasing stress intensity, and since these cells have a low wall/lumen ratio, they appear to have counterbalanced the increased amount of fibre wall substance.

Since both trees examined exhibited well above average density values at the periphery, it was hypothesised that these trees apparantly required no additional mechanical support tissue on the tension side of the lean. To test this hypothesis, a third leaning tree showing much lower density values, was examined. In this case a highly significant positive relationship was found.

In both tree fibre length increased with an increase in stress intensity. Although the correlation coefficients were not statistically significant, fibre length in both trees increased with increasing stress intensity.

In the second part of the study an attempt was made to distinguish between trees containing high from those with low levels of stress on the basis of their anatomical

and physical wood properties, heartwood content, stem taper, pith eccentricity and ovality. The prime object of this study was to establish to what extent between tree variation in wood properties could be explained in terms of differences in growth stress levels, and whether the growth stress/wood property relationships are similar to those observed within individual trees.

The trees used were selected from the same environment to minimize possible environmental effects. To avoid complications as a result of the presence of tension wood, two precautionery measures were taken: firstly, only straight trees with erect stems were selected for the study, and secondly, samples for studying the anatomical and physical properties of the wood were taken in a radius away from the maximum radius.

No significant difference in heartwood content was found between high- and low-stressed trees. This indicated that heartwood content and stress intensity could be manipulated independently in a tree improvement programme without one affecting the other.

This finding is of considerable importance to the wood preservation industry. The heartwood of *Eucalyptus grandis* contains extractives non-toxic to fungi and insects, and as a result, it is low in durability. Due to the presence of gum deposits and other blocking substances, mainly tyloses, the wood is also very difficult to impregnate. Since sapwood absorbs preservatives quite readily, a large proportion of sapwood is preferred for poles and other outdoor products to ensure sufficient protection against fungal decay and insect attack.

On the other hand, a large proportion of heartwood, which is more deeply coloured, may be preferred in many uses where colour is of importance. In view of the increasing worldwide shortage of timbers traditionally used for joinery and furniture, there is a growing demand in South Africa the local production of such timbers.

Eucalyptus grandis, although presently lacking in some required qualities, is well suited to replace many timbers in some joinery applications and furniture products. Since an attractive appearance is one of the important properties required for these purposes, the genetic manipulation for increased heartwood content would be of growing importance.

Even though straight and vertical growing trees were selected for this study, eccentric growth and ovality were present to varying degrees at all heights above ground level examined. Since conventional sawmilling practices are geared towards the production of sawn products from straight logs of average form, log parameters such as crook, sweep, ovality and pith eccentricity have an important influence on sawn yield and product quality. Poor log form not only result in low conversion efficiency, but boards are also of a lower quality as a result of the presence of cross grain defects, reaction wood and other associated defects.

Since no relationship was found between growth stress and the above mentioned log parameters, breeding efforts aimed at improving stem form of normal, vertical trees would not have any detrimental effect on the level of growth stress in trees, and *vice versa*.

Wood density, which is a measure of the amount of wood substance per unit volume, is regarded by many as one of the best single indicators of wood quality. Since it is dependent on several anatomical features like cell size, wall thickness and lumen diameter, proportion of various cell types and fractional wall volume of support tissue, such as tracheids and fibres, it follows that wood density is the most important single factor determining yield and pulp quality. It is also reasonable closely related to various wood properties and properties of sawing, machining, gluing, preservation of wood. It has also been shown to be heritable in many species (Burley, 1982).

In all trees examined, basic density increased rapidly from pith to bark, but in high-stressed trees these increases were more pronounced. This resulted in a considerable difference in basic density among high- and low-stressed trees, which increased in contrast towards the bark.

Results of various studies on *Eucalyptus grandis* have shown that the widely held opinion that faster diameter growth results in reduced wood density, does not apply for this species (Bamber and Humphreys, 1963; Bamber *et al.*, 1969; Bamber *et al.*, 1982; Taylor, 1973). Since the high-stressed trees were in fact shown to be faster growers, there seems to be sufficient evidence to believe that the tendency of high-stressed trees to produce denser wood, is a function of growth stress intensity and not rate of growth.

It can, therefore, be concluded that any attempt to increase volume production by silvicultural and/or genetic means will have little or no effect on growth stress intensity or wood density.

The close association found between wood density and growth stress intensity, suggests that the genetic manipulation of the one may have an effect on the other. The selection for reduced growth stress level may, for example, have a beneficial effect on within tree uniformity in wood quality, but may also reduce the overall density at the same time. While the first is a very much sought requirement by most manufacturers, the significance of the latter will depend entirely on the quality requirements of the end-product.

Differences in the fractional wall volume of fibres accounted for the difference in wood density, especially in the outer parts if the stem where considerable differences in the fractional wall volume were observed. However, both vessels and parenchyma have low cell wall/lumen ratios and may have an important bearing on wood density. The combined volumes of these tissue types were significantly lower in radial positions 2 and 3 of high-stressed

trees, and this may account for the differences in wood density observed in these positions. It must be borne in mind, however, that the association between wood density and the combined volume of vessels and ray parenchyma, may have been obscured by variations in the volume of the usually thin-walled axial parenchyma, since the latter had been considered together with the fibres. Considerable within- and in between-tree variation in axial parenchyma were previously reported for this species (Taylor, 1973).

The amount of collapse was found considerably less in high-stressed trees. The difference in the amount of collapse between high- and low-stressed trees may partly account for the wide variation in the seasoning behaviour often observed in boards originating from a particular tree, as well as from different trees. Fortunately, most collapse in normal wood can be removed by reconditioning the timber. This process involves the steaming of the dry timber for several hours in saturated steam at 100°C. This procedure appears to be less effective to rectify collapse in tension wood.

Based on observations made on Beech, Leclercz (1980) emphasized that wood density should not be used as an exclusive estimator of wood quality. His studies, as well as many others emphasized that the properties of defect free wood is ultimately determined by its anatomical properties and chemical composition (Burley, 1982; Nguyen van Thua, Tatishvili; Prawirohatmodjo, as reported by Hillis, 1980). Many of these studies have proved that anatomical analyses mathematically provide the best and most reliable estimates of the physico-mechanical properties of wood.

Apart from pulp yield, as determined by wood density and the pulping process employed, the pulp and paper industry is also concerned with the quality of the resulting fibres. This is determined by the pulping processes employed, as well as the morphological characteristics of the individual fibres.

The quality of paper is measured in terms of properties such as strength, density, porosity, surface quality, opacity, etc. These are determined by the intrinsic properties of the individual fibres, the distribution and form of fibres within the paper sheet, and the ability of adjacent fibre surfaces to form a bond with one another (Panshin and de Zeeuw, 1980).

In all trees examined, fibre length in general increased rapidly with increasing distance from the pith, but the pattern of variation differed from tree to tree. On average, high-stressed trees were found to produce longer fibres and to exhibit steeper pith to bark gradients in fibre length as compared to low-stressed trees. These differences, though small, were statistically significant.

Considerable among-tree differences in fibre length occurred, and since level if stress apparantly accounted for a significant proportion of this variation, it should be regarded of some practical significance in a tree improvement programme aimed at reducing level of growth stress.

Considerable evidence exists that paper properties are not determined by fibre length alone. Various other fibre properties are increasingly recognized having an important effect on paper properties. These are fibre diameter, wall thickness, lumen diameter and a number of arithmetic ratios such as the so-called fibre flexibility coefficient, felting coefficient, Mulsteph coefficient, Runkel ratio and fibre density.

Fibre density is one of the most important fibre properties affecting pulp yield and the quality of pulp and paper. It can either be expressed in terms of the thickness of the fibre wall or as the ratio of double-wall thickness to fibre diameter (Panshin and de Zeeuw, 1980). When expressed as a percentage, it is sometimes referred to as the Isenberg coefficient (Davidson, 1972).

Thick-walled fibres result in highly opaque, coarse and bulky papers with a high tear resistance, but being low in burst and tensile strength and folding endurance. Thin-walled fibres, on the other hand, result in dense, well bonded papers, being low in tear and high in tensile strength (Panshin and de Zeeuw, 1980).

Since the ratio of the double-wall thickness to fibre diameter expresses the relative proportion of wood substance in the cell cross-section, it correlates well with basic density. Thus, steep radial gradients occurred in all trees examined, while values obtained from the outer parts of the stem were significantly higher in trees containing high levels of growth stress.

Tensile strength and burst strength are directly determined by the degree of interfibre bonding, and decline with an increase in basic density (Higgens, 1978). The ratio of twice the wall thickness and lumen (known as the Runkel ratio) expresses the ability of fibres to collapse. This is an important property required for interfibre surface bonding during sheet formation. Thick-walled fibres are capable of maintaining their form to a larger extent than thin-walled fibres in the beating process, resulting in less surface area for interfibre contact and hence paper of lower strength properties. It is suggested that this ratio should be less than 1 for the manufacture of good quality paper because of the large surface contact which will be available for interfibre bonding after the beating process. Although ratios less than unity (as recommended by Runkel, 1952) occurred at most sampling positions, the results nevertheless imply that fibres originating from the outer parts of the stems of high-stressed trees will require more beating to meet the required interfibre surface bonding during sheet formation.

Available evidence on the effect of the ratio of fibre length to the diameter on paper strength, sometimes referred to as the felting coefficient, has been reviewed by Dinwoodie (1965) and Davidson (1972). Although some correlations with strength properties were found, many contradictions occurred in literature.

The flexibility coefficient was found to be significantly higher in the high-stressed stress at all radial sampling positions. This suggests that the longer fibres produced by high-stressed trees are not associated with a proportional increase in diameter.

Vessels are fairly large in this species and their size and frequency may have a significant effect on wood density, permeability, drying, painting, gluing, machining and the surface properties of paper (Hillis, 1978; Higgins, 1978). Vessel diameter has been found to increase and vessel frequency to decrease with increasing distance from the pith.

Significant differences were found in vessel size and frequency. Vessels were larger in diameter and slightly more abundant in high-stressed trees. As regards vessel diameter, differences appeared to be more pronounced in the central parts of the stem. Although the lower amount of conductive tissue in low-stressed trees might suggest implications for the pole preservation industry, differences in the outer parts of the stem were small and are, therefore, of little significance.

Differences in vessel size and frequency resulted only in small differences in vessel volumes between high- and low-stressed trees. Although vessels are inferior papermaking cells, differences in vessel volume were too small to be of much practical significance. Results of studies by Bamber *et al.* (1982) maintained that vessel volume can be reduced considerably by increasing the growth rate, without any effect on basic density and fibre length.

Ray volume was found considerably lower in high-stressed trees. Reduced ray width and increased ray spacing both accounted for the lower ray volume in high-stressed trees. As a result of the small differences in vessel volume found between the two groups of different stress intensities, reduced ray volume in high-stressed trees was accompanied by increased volume of mechanical support tissue (fibres).

8.6. Conclusion

Results of this study indicated marked differences and patterns in anatomical properties and wood density between trees containing widely different growth stress intensities. Results of analyses also suggest that trees of different stress levels may be separated on the basis of their anatomical properties using samples drawn at a convenient height above ground level in any one radius, provided trees are not leaning.

The results obtained indicated that the genetic reduction of the level of growth stress in a tree improvement programme would also result in reduced within- and between-tree variability in wood quality.

Because of the large number of anatomical features assessed in this study, and the large number of measurements that were needed to obtain reasonably accurate estimates, only a small number if trees could be studied. Hence, the results reported should not be regarded as representative without further investigation.

This study has set a basis for further investigation. It achieved to explain some of the extreme variation occurring in the properties and behaviour of wood within, as well as between trees of this species. It also provides guidelines urgently needed by tree breeders to minimise undesirable properties and to introduce qualities desired by the various avenues of wood utilization.

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CHAPTER NINE

SUMMARY AND FINAL CONCLUSIONS

In South Africa the hardwood processing industry relies heavily on locally grown species as a source of raw material for the production of mining timber, telephone and transmission poles, fencing materials and pulp. A considerable proportion of hardwood still has to be imported to meet the country's requirements for veneer, joinery and furniture because of the lacking quality of locally produced timber. As a result of rising shortages of hardwoods on the world market and the resultant increase in prizes, there is an increasing tendency among producers to turn to local sources for their raw material supply. As local hardwood is put to an increasing number of uses, there is a growing concern over the large variation in wood quality both within and between trees.

Of the many Eucalypts growing in South Africa, *Eucalyptus grandis* is economically by far the most important. However, the presence of high levels of growth stress, and a considerable between- and within-tree variation in commercially important properties such as wood density and fibre length, cause serious utilization problems and seriously limit the range of marketable products. As a result of this, large volumes of hardwood have to be imported to meet the local demand.

Studies indicated that a large proportion of imported timber for veneer and sleeper production, and for joinery purposes can be replaced by locally grown Eucalypt timber, provided the present quality problems, particularly the problems caused by high levels of growth stresses, can be solved.

The excellent tree characteristics of *Eucalyptus grandis* and its responsiveness to selective breeding have been emphasized in the thesis. It is generally recognized that many of the inferior wood qualities of this species can be improved by a well-planned breeding programme.

The origin of growth stress in trees, its nature, methods of control and the problems of timber conversion associated with high levels of stresses, have been reviewed extensively in this work.

Results of this study indicated that the level of growth stress in *Eucalyptus grandis* is not controlled by environmental factors to any great extent. Growth rate was found to be positively related to growth stress level, but this variable explained only a small proportion of the total variation among plantation grown trees. Large differences in splitting were observed between two sites of different soil qualities, which again pointed to rate of growth as a controlling factor of some importance. Although this result suggests that the reduction of growth rate through silvicultural means may result in a reduction of stress levels in trees, it is unlikely that the simultaneous loss in volume production would justify this in practice.

This study undoubtedly proved the existence of a seasonal fluctuation in the level of growth stresses in trees. While not quantitively proved by this study, there was some evidence that actively growing trees tend to develop higher levels of growth stress during periods of severe soil moisture shortage.

The availability of reliable genetic material of the species enabled an investigation of the genetic contribution towards the level of growth stress in trees. In material from two progeny trials, genetic variation had been detected for splitting, and therefore response to selection can be expected. The lack of relationship between growth stress level and the various tree parameters considered, especially rate of growth, suggests that selective breeding aimed at reducing level of growth stress and increasing volume production, can be carried out simultaneously.

Marked differences in a number of anatomical properties and wood density were found between trees of widely different growth stress levels. This is of considerable importance because wood

density and fibre length are the most widely used indices for wood quality. Furthermore, relative small variations in wood anatomy can markedly affect the quality of paper.

Statistical comparisons of the two groups of trees trees studies, showed a number of highly significant differences in wood properties. From the results the following inferences were drawn:

1) High-stressed trees appeared to be characterized by higher wood density in the outer parts of the stem resulting in steeper pith-to-bark gradients. Since wood density is largely determined by the proportion of thick-walled fibres, this finding was in agreement with the strong association found between peripheral stress level and the proportion of thick-walled fibres in leaning trees (Nicholson *et al.*, 1975).

   This suggests that the reduction of stress levels in trees would result in lower wood density in the outer parts of the stem and, as a consequence, a reduced cross-sectional variation in wood quality. Furthermore, a reduction in density gradient would be beneficial because it is maintained that the timber in the outer parts of the stem of this species is too heavy and too difficult to work for general utility purposes.

   Results of this study indicated that a reduction in wood density might lead to an increased tendency to collapse. This, however, should not render any serious difficulty in practice since high temperature steaming has proved to be quite efficient in rectifying collapsed timber.

2) Fibres were found to be longer in high-stressed trees and also appeared to exhibit a more pronounced increase in length from the pith outwards. This implies that a breeding programme aimed at reducing the levels of growth

stress in trees, might result in a slight reduction in fibre length but with less within-tree variability. Since log end-splitting is of no concern to the pulp producer, this offers a good opportunity to improve pulp quality and yield from fast-growing short rotation pulpwood plantations.

3) Apart from fibre length, a number of other fibre characteristics were found to be related to level of growth stress. Fibre wall thickness, the ratio of cell wall thickness to lumen diameter, and fibre diameter were all greater in trees of high stress intensities, mainly in the outer parts of the stem. Since all these properties contribute to pulp and paper characteristics (mainly strength), selection towards increased stress levels in the present short rotation selection programme seems to be advisable.

4) Significant differences were found in vessel size and frequency. Vessels were larger in diameter and slightly more abundant in high-stressed trees. As regards vessel diameter, differences appeared to be more pronounced in the central parts of the stem. Although the lower amount of conductive tissue in low-stressed trees could have certain implications for the pole preservation industry, differences in the outer parts of the stem were small and, as a result, of little practical significance.

Differences in vessel size and frequency resulted only in small differences in vessel volumes between high- and low-stressed trees. Although vessels are inferior papermaking cells, differences in vessel volumes were too small to be of any concern. In any case, studies by Bamber *et al.* (1982) maintained that vessel volume can be reduced considerably by increasing the rate of growth.

5) Ray volume was found considerably lower in high-stressed trees and was due to reduced ray widths and frequency.

6) Differences in vessel volume between the two stress groups of trees studied were found negligible.

7) Trees containing high levels of stress were characterised by increased volumes of support tissue (fibres). This suggests that selection for increased level of growth stress in trees in a short rotation breeding programme, as proposed earlier, may lead to increased fibre production per unit plantation area. Increased fibre volume, as well as increased fractional wall volume of fibres, were reflected by the density difference observed between the two groups of study trees.

Although the genetic reduction of growth stress levels in South African grown *Eucalyptus grandis* appears to be very promising, it must be emphasized that this may be a long-term effort. In the mean time, present research efforts must continue in order to find ways and means to maximize recovery and improve product quality from existing raw material.

In this work it was not intended to provide answers or solutions to all the inferior qualities of this species. The main purpose of this study was to add to the already existing basic knowledge in the aspects surrounding the problem of high growth stress levels. It was envisaged that the results of this study would contribute towards developing an even more efficient tree improvement programme, and also to indicate important areas of future research.

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BIBLIOGRAPHY

Altman, J.A., 1966. Modern methods of harvesting forest products. *Southern Lumberman, 213 (2656): pp. 131 - 135.*

Andrews, E.T.E., 1961. Saligna seed selection by the grower. *Letter to editor, Journal of the South African Forestry Association, No. 39, pp. 25 - 26.*

Archer, R.R. and Byrnes, F.E., 1972. On the distribution of growth stresses. I. A cylindrically anisotropic plane strain model. *Tec. Rept. No. EM. 72 - 73, Civil Engineering Dept., Univ. of Mass., Amherst, Mass.*

Archer, R.R. and Byrnes, F.E., 1974. On the distribution of tree growth stresses. Part I: An anisotropic plane strain theory. *Wood Science and Technology, Vol. 8, No. 3, pp. 184 - 196*

Archer,R.R., 1976. On the distribution of tree growth stresses. Part II: Stresses due to asymmetric growth strains. *Wood Science and Technology, Vol. 10, No. 4, pp. 293 - 309.*

Archer, R.R., 1979. On the distribution of tree growth stresses. Part III. The case of inclined grain. *Wood Science and Technology, Vol. 13, No. 1, pp. 67 - 78.*

Arganbright, D.G.; Bensend, D.W. and Manwiller, F.G., 1970. Influence of gelatinous fibres on the shrinkage of Silver Maple. *Wood Science, Vol. 3, No. 2, pp. 83 - 89*

Aung, M., 1962. Density variation outwards from the pith in some species of Shorea and its anatomical basis. *Empire Forestry Review, Vol. 41(1), No. 107, pp. 48 - 56.*

Bamber, R.K. and Humphreys, F.R., 1963. A preliminary study of some wood properties of *Eucalyptus grandis* (Hill) Maiden. *Journal of the Institute of Wood Science, No. 11, pp. 66 - 70.*

Bamber, R.K. and Curtin, R.A., 1974. Some properties of the wood in Blackbutt trees of two ages. *Australian Forestry, Vol. 36, No. 3, pp. 226 - 234.*

Bamber, R.K.; Floyd, A.G. and Humphreys, F.R., 1969. Wood properties of flooded gum. *Australian Forestry, Vol. 33, No. 1, pp. 3- 12.*

Bamber, R.K.; Horne, R. and Graham-Higgs, A., 1982. Effect of fast growth on the wood properties of *Eucalyptus grandis. Australian Forest Research, Vol. 12, No. 2, pp. 163 - 167.*

Bandyopadhyay, N. and Archer, R.R., 1979. Relief of growth stresses in planks. *Holzforschung, Bd. 33, H. 2, pp. 43 - 46.*

Banks, C.H. and van Vuuren, N.J.J., 1976. Selection of Eucalypt trees with regard to splitting in the sawn timber. *South African Forestry Journal, No. 99, pp.49 - 52.*

Barefoot, A.C. (jr), 1965. Influence of cellulose, lignin and density on toughness of Yellow Poplar. *Forest Products Journal, Vol. 15, No. 1, pp. 46 - 49.*

Barnacle, J.E. and Gottstein, J.W., 1968. Control of end splitting in round timber - a promising new method. *C.S.I.R.O., Div. Forest Prod., Tech. note no. 4, Melbourne, Australia.*

Barnacle, J.E. and Christensen, F.J., 1968. Pole timbers and their drying as factors of forest utilization. *Ninth British Commonwealth Forestry Conference.*

Barnacle, J.E., 1970. The incidence and development of felling damage in round timber. *Australian Forestry, Vol. 34, No. 3, pp. 161 - 169.*

Barnacle, J.E., 1971. Rapid effect of drying stresses on development of heart cracks. *Australian Forestry, Vol. 35, No. 4, pp. 251 - 257.*

Barnacle, J.E., 1971. Notes on felling damage and its interaction with tree growth stresses. *Symposium on the effect of tree injuries, felling and growth stresses on log quality and timber utilization. Section 41, IUFRO at Gainsville, Florida, U.S.A.*

Barnacle, J.E. and Necesaný, V., 1972. Impact damage in felled trees. Some notes with specific reference to ring shake. *C.S.I.R.O. Aust., Forest. Prod. Lab., Technol. Pap. No. 64.*

Barnacle, J.E., 1973. Cracking in round timber: A discussion about causes with special reference to impacts. *C.S.I.R.O. Aust., For. Prod. Lab., Div. Build. Res., Technol. Pap. No. 68, pp. 1 - 13.*

Base, G.D., 1955. Further notes on the Demec, a demountable mechanical strain gauge for concrete structures. *Magazine of Concrete Research, Vol. 7, No. 19, pp. 35 - 38.*

Beck, J.L., 1974. Anisotropic theory of growth stresses in trees. *Phys. and Engr. Lab., Dept. Sci. and Ind. Res., Lower Hutt, New Zealand, Rep. 452, 32pp.*

Belozerov, E.J.; Goldberg, A.M. and Orlov, S.F., 1960. "Research of the processes involved in a tree falling on to two supports" *Les. Prom., Vol. 2, pp. 19 - 20.*

Ben-Yehoshua, S. and Aloni, B., 1974. Effect of water stress on ethylene production by detached leaves of valencia orange (Citrus sinersis, Osbeck) *Plant Physiology.Vol. 53, pp. 863 - 865.*

Berlyn, G.P., 1961. Factors affecting the incidence of reaction tissue in *Populus deltoides* Bartr. *Iowa State Journal of Science, Vol. 35, No.3, pp. 367 - 424.*

Bielczyk, S., 1953. "The influence of some factors on splitting of Beech timber". *Instytut Badawczy Lesnictwa, Warszawa, No. 89.*

Bingham, R.T.; Squillace, A.E. and Wright, J.W., 1960. Breeding blister resistant Western White pine. *Silvae Genetica, Bd. 9, H. 2, pp. 33 - 41.*

Bisset, I.J.L. and Dadswell, H.E., 1949. The variation in fibre length within one tree of *Eucalyptus regnans*, F.v.M. *Australian Forestry, Vol. 13, No. 1, pp. 86 - 96.*

Bland, D.E., 1958. The Chemistry of reaction wood. Part I. The lignins of *Eucalyptus goniocalyx* and *Pinus radiata. Holzforschung, Bd. 12, H.2, pp. 36 - 43.*

Bland, D.E., 1961. The chemistry of reaction wood. Part III. The milled wood lignins of *Eucalyptus goniocalyx* and *Pinus radiata. Holzforschung, Bd. 15, H. 4, pp. 102 - 106.*

Bland, D.E. and Scurfield, G., 1964. The chemistry of reaction wood. Part IV. The distribution of the lignin in seedlings of hardwoods. *Holzforschung, Bd. 12, H. 1, pp. 161 - 166.*

Boyd, J.D., 1950. Tree growth stresses. Part I. Growth stress evaluation. *Australian Journal of Scientific Research, Series B, Vol. 3, No. 3, pp. 270 - 293.*

Boyd, J.D., 1950. Tree growth stresses. Part II. The development of shakes and other visual failures in timber. *Australian Journal of Applied Science, Vol. 1, No. 3, pp. 286 - 312.*

Boyd, J.D., 1950. Tree growth stresses. Part III. The origin of growth stresses. *Australian Journal of Scientific Research, Series B, Vol. 3, No. 3, pp. 294 - 309.*

Boyd, J.D. and Schuster, K.B., 1972. Tree growth stresses. Part IV. Visco-elastic strain recovery. *Wood Science and Technology, Vol. 6, No. 2, pp. 95 - 120.*

Boyd, J.D., 1972. Tree growth stresses. Part V. Evidence of an origin in differentiation and lignification. *Wood Science and Technology, Vol. 6, No. 4, pp. 251 - 262.*

Boyd, J.D., 1973. Compression wood generation and functional mechanics. *New Zealand Journal of Forestry Science, Vol. 3, No. 2, pp. 240 - 258.*

Boyd, J.D. and Foster, R.C., 1974. Tracheid anatomy changes as response to changing structural requirements of the tree. *Wood Science and Technology, Vol. 8, No. 2, pp. 91 - 105.*

Bredenkamp, B.V.; Malan, F.S. and Conradie, W.E., 1980. Some effects of pruning on growth and timber quality of *Eucalyptus grandis* in Zululand. *South African Forestry Journal, No. 114, pp. 29 - 34.*

Burley, J.; Posner, T. and Waters, P., 1970. Sampling techniques for measurement of fibre length in Eucalyptus species. *Wood Science and Technology, Vol.4, pp. 240 - 245.*

Burley, J., 1982. Genetic variation in wood properties. In: Baas, Pieter (Editor), *New perspectives in wood anatomy. Forest Science Series.* Martinus Nijhoff/Dr. W. Junk publishers, The Hague.

Burley, J. and Miller, F.B., 1982. The application of statistics and computing in wood anatomy. In: Baas, Pieter (Editor), *New perspectives in wood anatomy. Forest Science Series.* Martinus Nijhoff/Dr. W. Junk publishers, The Hague.

Chafe, S.C., 1977. Radial dislocations in the fibre wall of *Eucalyptus grandis* trees of high growth stresses. *Wood Science and Technology, Vol. 11, pp. 69 - 77.*

Chafe, S.C., 1981. Variation in longitudinal growth stress, basic density and modulus of elasticity with height in the tree. *Australian Forest Research, Vol. 11, No. 1, pp. 79 - 82.*

Chardin, A. and Sales, C., 1983. Species developing a high level of growth stresses: A method of measure and its possible use to study the consequence on wood quality. *Proceedings IUFRO V, Madison, Wisconsin.*

Chow, K.Y., 1946. A comparative study of the structure and chemical composition of tension wood wood and normal wood in Beech (*Fagus sylvatica* L.). *Forestry, Vol. 20, pp. 62 - 77.*

Chow, P., 1971. Fibre length variation in the bole of an eccentric Sweetgum tree. *Forest Science, Vol. 17, No. 2, pp. 186 - 189.*

Chudnoff, M. and Tischler, K., 1963. Fibre morphology of *Eucalyptus camaldulensis* Dehnh. and relation of wood anatomy to certain physical and mechanical properties. *La-Yaaran, Supp. No. 1.*

Clarke, S.H., 1937. The distribution, structure and properties of tension wood in Beech *(Fagus silvatica L.). Forestry, Vol. 11, No. 2, pp. 85 - 91.*

Clarke, S.H., 1939. Stresses and strains in growing timber. *Forestry, Vol. 13, No. 1, pp. 68 - 79.*

Cochran, W.G. and Cox, C.M., 1957. *Experimental Designs.* Second Edition. John Wiley and Sons, New York.

Conradie, W.E., 1980. Utilization of South African grown *Eucalyptus grandis* (W.Hill ex Maiden) as veneer logs. Part I. Control of end-splitting in veneer logs. *C.S.I.R. Special Report, Hout 206.*

Conway, S., 1969. Old idea offers new savings to timber firm. *Forest Industries, Vol. 96, No. 11, pp. 66 - 67.*

Cuevas, L.E., 1969. Shrinkage and collapse studies on *Eucalyptus viminalis. Journal of the Institute of Wood Science, Vol 4, No. 23, pp. 29 - 38.*

Currò, P. and Cividini, R., 1961. Preliminary observations on growths stresses in Eucalypts. *Second World Eucalyptus Conf., Sao Paulo, F.A.V.*

Cuznetov, A.I., 1950. Vnutrenie nepriajenii a v drevemizdat. Moscow, Goslesbumizdat.

Dadswell, H.E. and Langlands, I., 1934. Brittle heart in Australian timbers: A preliminary study. *Journal of Sci. Ind. Res., Australia, Vol. 7, No. 4, pp. 190 - 196.*

Dadswell, H.E. and Wardrop, A.B., 1949. What is reaction wood? *Australian Forestry, Vol. 13, No. 1, pp. 20 - 33.*

Dadswell, H.E. and Wardrop, A.B., 1955. The structure and properties of tension wood. *Holzforschung, Bd. 9, H. 4, pp. 97 - 104.*

Dadswell, H.E. and Wardrop, A.B., 1956. The importance of tension wood in timber utilization. *Australian Pulp and Paper Industry Technical Association Proceedings, Vol. 10. Division of Forest Products, Reprint No. 285, pp. 30 - 42.*

Dadswell, H.E. and Hillis, W.E., 1962. In: Hillis, W.E. (Editor), *Wood extractives and their significance to the Pulp and Paper Industry.* Academic Press, New York.

Dadswell, H.E.; Wardrop, A.B. and Watson, A.J., 1962. The morphology, chemistry and pulp characteristics of reaction wood. *Fundamentals of papermaking fibres. Tech. Sect., British Paper and Board Makers' Assoc. Inc., London, pp. 178 - 219.*

Davidson, J., 1972. Variation, association and inheritance of morphological and wood characters in an improvement programme for *Eucalyptus deglupta. Ph.D. Thesis, Australian National University, Canberra.*

Desch, H.E., 1981. Revised by J.M. Dinwoodie. *Timber: Its structure, properties and utilization. Sixth Edition.* The Macmillan Press Ltd., London.

De Villiers, A.M., 1973. Utilization problems with some Eucalypts in South Africa. *IUFRO V Proceedings, Vol.2, pp. 238 - 255. Cape Town and Pretoria, Republic of South Africa.*

Dinwoodie, J.M., 1965. The relationship between fibre morphology and paper properties: A review of literature. *Tappi, Vol. 48, No. 8, pp. 440 - 447.*

Dinwoodie, J.M., 1966. Growth stresses in timber: A review of literature. *Forestry, Vol. 39, No. 2, pp. 162 - 170.*

Edwards, D.W., 1973. Defects in fast-grown Eucalyptus in New South Wales, Australia. *IUFRO V Proceedings, Vol. 2, pp. 256 - 270. Cape Town and Pretoria, Republic of South Africa.*

El-Beltage, A.S. and Hall, M.A., 1974. *New Phytol., Vol. 73, pp. 47.*

Esau, K., 1965. *Plant Anatomy. Second Edition.* John Wiley and Sons, New York.

Ferrand, J. Ch., 1982. Growth stresses and silviculture of Eucalypts. *Australian Forest Research, Vol. 13, No.1, pp. 75 - 81.*

Fraser, A.I., 1962. The soil and roots as factors in tree stability. *Forestry, Vol. 35, No. 1, pp. 117 - 127.*

Fraser, A.I., 1963. Wind tunnel studies of the forces acting on the crowns of small trees. *G.B. Forestry Commision, Annual Research Report, pp. 178 - 183.*

Freese, Frank, 1974. Elementary statistical methods for foresters. *USDA Agricultural Handbook, No. 317, 87pp.*

Furuya, N.; Takahashi, S. and Miyazaki, M., 1970. The chemical compositions of gelatinous layer from the tension wood of *Populus euro-americana*. *Mokuzai Gakkaishi, Vol. 16, No. 1, pp. 26 - 30.*

Gillis, P.P. and Burden, A.K., 1972. Heart shakes and growth stresses. *Wood and Fibre, Vol. 4, No. 2, pp. 95 - 98.*

Gillis, P.P., 1973. Theory of growth stresses. *Holzforschung, Bd. 27, H. 6, pp. 197 - 207.*

Gillis, P.P. and Hsu, C.H., 1979. An elastic, plastic theory of longitudinal growth stresses. *Wood Science and Technology, Vol. 13, No. 2, pp. 97 - 115.*

Giordano, G. and Ghisi, G., 1965. Contribution to the study of growth stresses in Eucalyptus. *IUFRO Section 41, Melbourne, Australia.*

Giordano, G.; Currò, P. and Ghisi, G., 1969. Contribution to the study of internal stresses in the wood of Eucalypts. *Wood Science and Technology, Vol. 3, No. 1, pp. 1 - 13.*

Giordano, G., Currò, P., 1972. A propos des tensions internes dans les arbres, les grumes et les sciages. *Bois et Forêsts des Tropiques, No. 145, pp. 39 - 48.*

Giordano, G. and Currò, P., 1973. Observations concerning unusual methods for reducing damage from growth stresses in Eucalyptus sawn timber. *IUFRO V Proceedings, Cape Town and Pretoria, Republic of South Africa.*

Goebel, N.D.; Taras, M.A. and Smith, W.R., 1960. Tension wood and its relation to splitting in Hickory. *South Carolina Agricultural Experiment Station, Bull. 480, Clemson, South Carolina.*

Grozdits, G.A. and Ifju, G., 1969. Development of tensile strength and related properties in differentiating coniferous xylem. *Wood Science, Vol. 1, No. 3, pp. 137 - 147.*

Hall, G.S., 1967. Some mechanical and nutritional aspects of cambial increment distribution in Red Pine. *Doctor of Forestry Thesis, Yale School of Forestry.*

Hallock, H., 1974. Growth stresses and lumber warp in Loblolly Pine. *Forest Products Journal, Vol. 16, No. 2, pp. 48 - 52.*

Hans, A.S.; Burley, J. and Williamson, P., 1972. Wood quality of *Eucalyptus grandis* (Hill) Maiden grown in Zambia. *Holzforschung, Bd. 26, H. 4, pp. 138 - 141.*

Hardie, A.D.K. and Wood, A.A., 1973. *Eucalyptus grandis* timber from plantations in Zambia. *Commonwealth Forestry Review, Vol. 52, No. 2, pp. 152 - 159.*

Hardie, A.D.K., 1974. Defects in the wood of fast-grown *Eucalyptus grandis* in Zambia. *Commonwealth Forestry Review, Vol. 53, No. 4, pp. 310 - 317.*

Higgens, H.G., 1978. Pulp and Paper. In: Hillis, W.E. and Brown, A.G. (Editors), *Eucalypts for wood production.* Part G. Commonwealth Scientific and Industrial Research Organization, Australia.

Higgs, M.I., 1969. Genetic and environmental factors influencing commercially important wood properties of *Eucalyptus grandis. Ph.D. Thesis, Australian National University, Canberra.*

Hillis, W.E., 1969. The contribution of polyphenolic wood extractives to pulp. *Appita, Vol. 23, pp. 89 - 101.*

Hillis, W.E., 1973. Defects in fast-grown Eucalypts. *Introductory paper to working party 5.01.9. IUFRO V Proceedings, Cape Town and Pretoria, Republic of South Africa,*

Hillis, W.E.; Hardie, A.D.K. and Ilic, Y., 1973. The occurrence of brittle heart in *Eucalyptus grandis* grown in Zambia. *IUFRO V Proceedings, Cape Town and Pretoria, Republic of South Africa.*

Hillis, W.E., 1975. Ethylene and extraneous material formation in woody tissues. *Phytochemistry, Vol. 14, pp. 2559 - 2562.*

Hillis, W.E., 1978. Wood quality and utilization. In: Hillis, W.E. and Brown, A.G. (Editors), *Eucalypts for wood production.* Part G. Commonwealth Scientific and Industrial Research Organization, Australia.

Hillis, W.E., 1980. Some basic characteristics affecting wood quality. *Appita, Vol. 33, No. 5, pp. 339 - 344.*

Hodgson, L.M., 1967. The breeding of Eucalypts in South Africa. Forestry of South Africa, No. 8, pp. 31 - 42.

Hodgson, L.M., 1974. The breeding of Eucalyptus in South Africa. *South African Forestry Journal, No. 89. pp. 13 - 15.*

Hodgson, L.M., 1975. Some aspects of reproductive behaviour in *Eucalyptus grandis* (Hill) Maiden. *Unpublished D.Sc. Thesis, Department of Botany, Unversity of Pretoria.*

Holz, P., 1967. South African operation cuts Eucalyptus. *World Wood, Vol. 8, No. 2, pp. 6 - 7.*

Höster, H., 1972. On the anatomy and histology of reaction wood in *Salix cuprea* L. *Ber. Dtsch. Bot. Ges., Vol. 85, No. 7/9, pp. 459 - 465.*

Hughes, J.H., 1965. Tension wood: A review of the literature. *Forestry Abstracts, Vol. 26, pp. 1 - 16.*

Imam, M. El-S and Heikal, I. A-M., 1972. A study on the elimination or reduction of splitting of *Eucalyptus camaldulensis. Agricutural Research Review, Egypt, No. 56, pp. 189 - 198.*

Isebrands, J.G. and Bensend, D.W., 1972. Incidence and structure of gelatinous fibres within rapid-growing Eastern Cottonwood. *Wood and Fibre, Vol. 4, No. 2, pp. 61 - 71.*

Jaccard, P., 1938. Exzentrisches Dickenwachstum und anatomish-histologische differenzierung des Holzes. *Ber. der Schweiz. Bot. Ges., Vol. 48, pp. 491 - 537.*

Jacobs, M.R., 1937. Notes on movements in Eucalyptus trunks. *Australian Forestry, Vol. 2, No. 2, pp.14 - 18.*

Jacobs, M.R., 1938. The fibre tension of woody stems with special reference to the genus Eucalyptus. *Commonwealth Forestry Bureau of Australia, Bulletin 22, Canberra.*

Jacobs, M.R., 1939. Further studies on fibre tension. *Commonwealth Forestry Bureau of Australia, Bulletin 24, Canberra.*

Jacobs, M.R., 1945. The growth stresses of wood stems. *Commonwealth Forestry Bureau of Australia, Bulletin 24, Canberra.*

Jacobs, M.R., 1955. Growth habits of the Eucalypts. *Forestry and Timber Bureau, Canberra.*

Jacobs, M.R., 1965. Stresses and strains in tree trunks as they grow in length and width. *Commonwealth of Australia, Dept. of National Development, Forestry and Timber Bureau, Leaflet no. 96, Canberra.*

Jayme, G., 1951. "On the significance of tension wood portion in Poplars". *Holz als Roh- und Werkstoff, Bd. 9, H. 5, pp. 173 - 175.*

Jayme, G. and Harders-Steinhäuser, M., 1953. Zugholz und seine Auswirkungen in Pappel-und-Weidenholz. *Holzforschung, Bd. 7, H. 2/3, pp. 39 - 43.*

Johnston, J.S., 1968. Crosscutting trees and logs by shear blades. *Southern Lumberman, 217(2698), pp. 39, 40, 41, 44 and 46.*

Kaeiser, M. and Pillow, M.Y., 1955. Tension wood in Eastern Cottonwood. *Central States Forest Experiment Station, Paper no. 149.*

Kaeiser, M., 1955. Frequency and distribution of gelatinous fibres in Eastern Cottonwood. *American Journal of Botany, Vol. 42, pp. 331 - 334.*

Kaeiser, M. and Boyce, S.G., 1965. The relationship of gelatinous fibres to wood structure in Eastern Cottonwood (*Populus deltoides*). *American Journal of Botany, Vol. 52, No. 7, pp. 711 - 715.*

Kandeel, E.S.A.; Badran, O.A. and Tewfik, S.A., 1977. Sampling for fibre length in small tropical hardwood samples. *Wood Science, Vol. 9, No. 3, pp. 140 - 143.*

Kauman, W.G., 1958. The influence of drying stresses and anisotropy on collapse in *Eucalyptus regnans*. *C.S.I.R.O., Division of Forest Products, Technical Paper no. 3, Australia.*

Kelsey, K.E. and Kingston, R.S.T., 1957. The effect of specimen shape on the shrinkage of wood. *Forest Products Journal, Vol. 7, No. 7, pp. 234 - 235.*

Kikata, Y., 1972. The effect of lean on level of growth stress in *Pinus densiflora*. *Mokuzai Gakkaishi, Vol. 18, No. 9, pp. 443 - 449.*

Kikata, Y., 1974. Growth stress of Tropical Wood. *Mokuzai Kigyo (Wood Industry), Vol. 29, No. 3, pp. 17 - 19.*

Kikata, Y., 1974. Growth stress of Tropical Wood (2). *Mokuzai Kigyo (Wood Industry), Vol. 29, No. 5, pp. 16 - 19.*

Koch, C.B. and Hamilton, J.R., 1968. The nature of tension wood in Black Berry. *Bulletin 561, West Virginia Unversity, Agric. Exp. Sta.*

Koehler, A., 1933. A new hypothesis as to the causes of shakes and rift cracks in green timber. *Journal of Forestry, Vol. 31, No. 5, pp. 551 - 556.*

Korzenjowski, A.M., 1970. Investigation of the longitudinal growth stress magnitude and distribution in *Eucalyptus grandis* stems. *Unpublished Report from division of Forest Products Research, Zambia.*

Krogh, P. 1982. Dwarslêers van gelamineerde Suid-Afrikaanse dennehout. *South African Forestry Journal, No. 122, p. 52.*

Kromhout, C.P., 1983. Preservation and conservation. *Wood Preservation Symposium, National Timber Research Institute, C.S.I.R., Pretoria.*

Kübler, H., 1959. "Studies on growth stresses in trees. Part 1. The origin of growth strains and stresses in the transverse direction". *Holz als Roh- und Werkstoff, 17.Jg., H. 1, pp. 1 - 9. C.S.I.R.O., Australia. Translation no. 4542(A).*

Kübler, H., 1959. "Studies on growth stresses in trees. Part 2. Longitudinal stresses". *Holz als Roh- und Werkstoff, 17.Jg., H. 2, pp. 44 - 54. C.S.I.R.O., Australia. Translation no. 4542(B).*

Kübler, H., 1959. "Studies on growth stresses in trees. Part 3. Effect of heat treatment on the dimensions of green wood". *Holz als Roh- und Werkstoff, 17.Jg., H. 3, pp. 77 - 86. C.S.I.R.O., Australia. Translation no. 4542(C).*

Larson, P.R., 1963. Evaluating the environment for studies of the inheritence of wood properties. *World Consulation on Forest Genetics and Tree improvement, Stockholm. FAO of the United Nations, Rome.*

LeClercq, A., 1980. Relationship between Beechwood anatomy and its physico-mechanical properties. *IAWA Bulletin n.s., Vol. 1, No. 1 - 2, pp. 65 - 71.*

Lenz, O. and Strässler, H., 1959. "Notes on the splitting of Beech logs (*Fagus sylvatica)". Schweizerische Anstalt für das Forstliche Versuchswesen, Vol. 35, No. 5, pp. 373 - 409. C.S.I.R.O., Australia. Translation no. 6430.*

Lieberman M. and Kunishi, A.T., 1970. Thoughts on the role of ethylene in plant growth and development. *Plant Growth Substances. Editor D.J. Carr.*

Lubbe, W.F., 1980. Survey of the exotic hardwood industry in South africa. *C.S.I.R. Special Report, Hout 198.*

Lückhoff, H.A., 1967. Pruning of *Eucalyptus grandis. Forestry in South Africa, No. 8, pp. 75 - 85.*

Mackay, J.F.G., 1972. The occurrence, development and control of checking in Tasmanian *Eucalyptus obliqua. Holzforschung, Bd. 26, H. 4, pp. 121 - 124.*

Maeglin, R.R. and Boone, R.S., 1981. Manufacturing quality structural timber from hardwoods using the Saw-Dry-Rip process. *Proceedings Ninth Annual Hardwood Symposium of the Hardwood Research Council, Pipestem state Park, Pipestem, West Virginia, pp. 29 - 45.*

Malan, F.S., 1979a. "A general study on log end-splitting in South African grown *Eucalyptus grandis* (W. Hill ex Maiden)." *Unpublished M.Sc. Thesis, University of Stellenbosch.*

Malan, F.S. 1979b. The control of end-splitting in saw logs: A short literature review. *South African Forestry Journal, No. 109, pp. 14 - 18.*

Malan, F.S. and Toon, R.E., 1980. Natural defects in the timber of South African grown Pinus and Eucalyptus species. *Pamphlet no. 250, Department of Environmental Affairs.*

Manseau, A., 1979. Rapid methods for determining green volume and basic specific gravity. *Wood Science, Vol. 12, No. 2, pp. 98 - 99.*

Manwiller, F.G., 1967. Tension wood anatomy of Silver Maple. *Forest Products Journal, Vol. 17, No. 1, pp. 43 - 48.*

Margadant, R.F., 1981. Why not peel locally grown Eucalyptus? *Wood Southern Africa, Vol. 6, No. 10, p. 8.*

Marsh, E.K., 1953. How to distinguish between *Eucalyptus saligna* Sm. and *Eucalyptus grandis* (Hill ex Maiden). *The Journal of the South African Forestry Association, No. 23, pp. 37 - 44.*

Marsh, E.K. and Burgers, T.F., 1867. The relation between silvicultural treatment and timber quality in *Eucalyptus grandis*. *Forestry in South Africa, No. 8, pp. 63 - 74.*

Marsh, E.K. and Haigh, H., 1963. Preliminary results from provenance trials with *Eucalyptus saligna* Sm. and *Eucalyptus grandis* (Hill) Maiden. *Forestry in South Africa, no. 2, pp. 127 - 131.*

Martley, J.F., 1928. Theoretical calculations of the pressure distribution on the basal section of a tree. *Forestry, Vol. 2, No. 1, pp. 69 - 72.*

Mayer-Wegelin, H. and Mammen, E., 1954. Spannungen und Spannungsrisse im Buchenstammholz. *Allgemeine Forst- und Jagdzeitung, Vol. 125, No. 9, pp. 287 - 297.*

Mayer-Wegelin, H., 1955. "Tensions and tension splitting in standing and felled logs". *Mitteilungen der Osterreichischen Gesellschaft für Holzforschung, Vol. 7, No. 2, pp. 11 - 17. C.S.I.R.O., Australia. Translation No. 2749.*

McIntosh, J.A. and Kerbes, E.L., 1969. Tree shears reduce felling costs, offer other savings. *Canadian Forest Industries, Vol. 88, No. 3, pp. 42 - 47.*

McMichael, B.L.; Jordan, W.R. and Powell, R.D., 1972. *Plant Physiology, Vol. 49, pp. 658.*

Meylen, B.A., 1968. Cause of high longitudinal shrinkage in wood. *Forest Products Journal, Vol. 18, No. 2, pp. 75 - 78.*

Mia, A.J., 1968. *Bi-monthly Research Notes, Dept. Forestry Rural Development, Ottowa, Canada, Vol. 23, No. 13, pp. 24.*

Michael, M. and Shite, D.E., 1956. The chemistry of Western Australian plants. IX. Extractives from the timber of *Eucalyptus diversicolor* F. Muell. *Australian Journal of Applied Science, Vol 6, pp. 359 - 364.*

Morice, P.B. and Base, G.D., 1953. The design and use of the demountable mechanical strain gauge for concrete structures. *Magazine of Concrete Research, Vol. 5, No. 13, pp. 1 - 6.*

Münch, E., 1938. Statik und Dynamik des schraubigen Baus der Zellwand, besonders des Druck- und Zugholzes. *Flora, Vol. 32, pp. 357 - 424.*

Narayanamurti, D.; Jain, N.C.; Gupta, R.C. and Pant, H.C., 1963. Growth stresses in trees. *Silvae Genetica, Bd. 12, , pp. 89 - 99.*

Naumov, D.L., 1956. Sushka bukovykh sagotovok v zazhatom sostoyanii. *Derevoob. Prom. (9), pp. 21 - 22.*

Nel, P.M., 1962. The breeding of Eucalypts in South Africa. *Journal of the South African Forestry Association, No. 54, pp. 17 - 21.*

Nelson, N.D., 1975. Extractives produced during heartwood formation in relation to amounts of parenchyma in *Juglans nigra* and *Quercus rubra. Canadian Journal of Forest Research, Vol 5, pp. 291 - 301.*

Nelson, N.D. and Hillis, W.E., 1978. Ethylene and tension wood formation in *Eucalyptus gomphocephala. Wood Science and Technology, Vol. 12, pp. 309 - 315.*

Nguyen and Thua, 1977. Variation in vessel characteristics of Eucalyptus dalrympheana Maiden associated with sample position, *growth rate and climatic changes. M.Sc. Thesis, Australian National University, Canberra.*

Nicholls, J.W.P. and Phillips, F.H., 1970. Preliminary study of coppice-grown *Eucalyptus viminalis* as a source of chip material. *C.S.I.R.O., Div. For. Prod., Tech. Pap. No. 58.*

Nicholson, J.E., 1970. Growth stress investigations in regrowth Eucalypts. *Newsletter 374, Forest Prod. Lab., C.S.I.R.O., Melbourne, Australia.*

Nicholson, J.E., 1971(a). A rapid method for estimating longitudinal growth stresses in logs. Wood Science and Technology, Vol. 5, pp. 40 - 48.

Nicholson, J.E., 1971(b). A study of longitudinal growth stress in *Eucalyptus regnans* regrowth. *Ph.D. Thesis, Australian National University.*

Nicholson, J.E.; Campbell, G.S. and Bland, D.E., 1972. Association between wood characteristics and growth stress level: a prelimanary study. *Wood Science, Vol. 5, No. 5, pp. 109 - 112.*

Nicholson, J.E., 1973(a). Effect of storage on growth stress in mountain Ash logs and trees. *Australian Forestry, Vol. 36, No. 2, pp. 114 - 124.*

Nicholson, J.E., 1973(b). Growth stress differences in Eucalyptus. *Forest Science, Vol. 19, No. 3, pp. 169 - 174.*

Nicholson, J.E.; Hillis, W.E. and Ditchburne, N., 1973(a). Growth stresses and anatomical characteristics in *Eucalyptus regnans. Proceedings of the 16th For. Prod. Res. Conf., Melbourne, Australia.*

Nicholson, J.E.; Barnacle, J.E. and Lesse, P.F., 1973(b). Evidence of residual stress in small sections of ordinary green *Eucalyptus regnans*. *Wood Science and Technology, Vol. 7, pp. 20 - 28.*

Nicholson, J.E.; Hillis, W.E. and Ditchburne, N., 1975. Some tree growth-wood property relationships of Eucalyptus. *Canadian Journal of Forest Research, Vol. 5, No. 3, pp. 424 - 432.*

Norberg, P.H. and Meier, H. 1966. Physical and chemical properties of the gelatinous layer in Tension Wood fibres of Aspen (*Populus tremula* L.). *Holzforschung, Bd. 20, H. 6, pp. 174 - 178.*

Okuyama, T. and Kikata, Y., 1975. The residual stresses in wood logs due to growth stresses. *Mokuzai Gakkaishi, Vol. 21, No. 6, pp. 335 - 341.*

Okuyama, T. and Sasaki, Y. 1979. Crooking during lumbering due to residual stresses in the tree. *Makuzai Gakkaishi, Vol. 25, No. 11, pp. 681 - 687.*

Okuyama, T.; Sasaki, Y.; Kikata, Y. and Kawai, N., 1981. The seasonal change in growth stress in the tree trunk. *Makuzai Gakkaishi, Vol. 27, No. 5, pp. 350 - 355.*

Olesen, P.O., 1971. The water replacement method: a fast and accurate method of determining the green volume of wood samples. *A paper from the Forestry Institute, The Royal Veterinary- and Agricultural University of Copenhagen.*

Orlov, L.E., 1975. "Calculations of stresses and strains in non-uniform material of woody plants". *Lesnoi Zhurnal, No. 2, pp. 90 - 93.*

Osborne, D.J., 1975. Ethylene as a natural regulator of the growth of plants. *Ann. Appl. Biol. 81, pp. 95 - 98.*

Panshin, A.J. and de Zeeuw, C., 1980. *Textbook of wood technology. Fourth edition.* McGraw-Hill Book Company, New York.

Parameswaran, N. and Liese, W., 1973. Variation of cell lengths in bark and wood of Tropical Trees. *IUFRO V Proceedings, Cape Town and Pretoria, Republic of South Africa.*

Patel, R.N., 1964. On the occurrence of gelatinous fibres with special reference to root wood. *Journal of the Institute of Wood Science, No. 2, pp. 67 - 80.*

Penfold, A.R. and Willis, J.F., 1961. *The Eucalypts: botany, chemistry, cultivation and utilization.* Leonard Hill (Books) Limited, London.

Perem, E., 1964. Tension wood in Canadian hardwoods. *Forest Products research Branch, Department of Forestry, Publication no. 1057, 38pp.*

Perkitny, T.; Wojcienchowski, E. and Wnuk, M., 1951. "Origination of shakes in Beech logs, analysis of causes and means of prevention". *Instytut Badawczy Lesnictwa, Warszawa, p. 68.*

Platon, V., 1959. "Internal stresses in Beechwood and means for their reduction". *Industria Lemnului, Vol. 7, No. 12, pp. 441 - 447. C.S.I.R.O., Australia. Translation no. 5468.*

Post, I.L., 1979. An Incremental longitudinal growth stress distribution model. *Holzforchung, Bd. 33, H. 4, pp. 107 - 111.*

Post, I.L.; Altherton, J.C.; Vendhan, C.P. and Archer, R.R., 1980. An extention of Jacobs' method for measuring residual growth strains in logs. *Wood Science and Technology, Vol. 14, pp. 286 - 296.*

Polge, H. and Thiercelin, F., 1979. Growth stress appraisal through increment core measurements. *Wood Science, Vol. 12, No. 2, pp. 86 - 92.*

Poynton, R.J., 1979. *Tree planting in Southern Africa. Vol. 2. The Eucalypts.* Report to the South African commission for the concervation and utilization of the soil. Department of Environmental Affairs, Republic of South Africa.

Prawirohatmodjo, S., 1977. An assessment of the properties and utilization of some secondary hardwood species of Indonesia. *Ph.D. Thesis, Australian National University, Canberra.*

Priest, D.T.; Knuffel, W.; Malan, F.S. and van Rensburg, M., 1981. The sawmilling and timber properties of 12- and 24-year-old plantation grown *E. grandis. C.S.I.R. Special Report, Hout 222.*

Priest, D.T.; Knuffel, W.E. and Malan, F.S., 1982. End-splitting in *E. grandis* sawlogs and sawn timber. *C.S.I.R. Special Report, Hout 223.*

Priest, D.T.; Singmin, M. and van Niekerk, J.P., 1984. The influence of sawing techniques on the occurrence of end-splitting and heart shake in *E. grandis* sawn timber. *C.S.I.R. Special Report, Hout 333.*

Priestly, J.H. and Tong, D., 1927. The effect of gravity upon cambial activity in trees. *Proc. Leeds. Phul. Soc. 1, pp. 119 - 208.*

Princess Risborough Laboratory, 1972. Reaction wood (tension wood and compression wood). *Technical Note No. 57, 20p.*

Ranatunga, M.S., 1964. A study of the fibre lengths of *Eucalyptus grandis* grown in Ceylon. *Ceylon Forester. No. 6, pp. 101 - 112.*

Robards, A.W., 1965. Tension wood and eccentric growth in Crack willow. *Ann. Bot. (London) (N.S.) Vol. 29, pp. 419 - 431.*

Robards, A.W., 1969. The effect of gravity on the formation of wood. *Sci. Prog. (London), No. 57, pp. 513 - 532.*

Rudman, P. *et al.*, 1969. Breeding Eucalyptus for wood properties. *Second World Consultation on Forest tree breeding, Washington D.C.*

Runkel, R., 1952. Pulp from tropical woods. *Zellwandforschung und Sell stoff-chemie, 29, pp. 1 - 77. F. Haller, Verlag, Berlin.*

Sasaki, Y.; Okuyama, T. and Kikata, Y., 1978. The evolution process of the growth stress in the tree. The surface stresses on the tree. *Mokuzai Gakkaishi, Vol. 24, No. 3, pp. 149 - 157.*

Sasaki, Y.; Okuyama, T. and Kikata, Y., 1981. Determination of the residual stress in a cylinder of inhomogeneous anisotropic material. *Mokuzai Gakkaishi, Vol. 27, No. 4. Part I, pp. 277 - 282. Part II, 270 - 276.*

Sass, J.E., 1940. *Elements of botanical micro-technique.* McGraw-Hill Book Company, Inc., New York.

Sauer, F.M.; Fons, W.L. and Arnold, K., 1951. Experimental investigation of aerodynamic drag on tree crowns exposed to steady wind - conifers. *U.S. Forest Service, Div. of Fire Research, Phase Rept., 119pp.*

Saurat, J. and Guéneau, P., 1976. Growth stresses in Beech. *Wood Science and Technology, Vol. 10, pp. 111 - 123.*

Scott, J.H., 1950. Die benutting van *Eucalyptus saligna* wat in Suid-Afrika gekweek word. *Pamphlet no. 34, Department of Environmental Affairs.*

Schwerin, G., 1958. The chemistry of reaction wood. Part 11. The polysaccharides of *Eucalyptus goniocalyx* and *Pinus radiata*. *Holzforschung, Bd. 12, H. 2, pp. 43 - 48.*

Scurfield, G., 1964. The nature of reaction wood. Part IX. Anomalous cases of reaction anatomy. *Australian Journal of Botany , Vol. 12, pp. 173 - 184.*

Scurfield, G., 1973. Reaction wood: its structure and function. *Science, 179, pp. 647 - 655.*

Sinnott, E.W. 1952. Reaction wood and the regulation of tree form. *American Journal of Botany, 39, pp. 69 - 78.*

Skolmen, R.G., 1967. Heating logs to relieve growth stresses. *Forest Products Journal, Vol. 17, No. 7, pp. 41 - 42.*

Skolmen, R.G., 1972. Specific gravity variation in *Eucalyptus robusta* grown in Hawaii. *U.S. For. Serv. Pacif. Sthwest. For. Range Exp. Sta. Res. Pap. PSN-78.*

Sokal, R.R. and Rohlf, F.J., 1969. *Biometry: The principles and practice of statistics in biological research.* W.H. Freeman and Company, San Fransisco.

Steele, J.H.; Ifju, G. and Johnson, J.A., 1976. Quatitative characterisation of wood microstructure. *Journal of Microscopy, Vol. 107, Pt. 3, pp. 279 - 311.*

Stern-Cohen, S. and Fahn, A., 1964. Structure and variation of the wood fibres of *Eucalyptus gomphocephela* A.D. along and across the stem. *La-Yaaran, Vol. 14, No. 4, pp. 106 - 116.*

Streets, R.J., 1962. *Exotic forest trees in the Commonwealth.* Claredon Press, Oxford.

Strikha, I.A., 1954. Prichiny deformatsii detaley iz drevesiny i sposoby ee umenskeniya. *Derevoobrabatywajuscaji i lesochimiceskaja promyslennost, Vol. 3, No. 7, pp. 7 - 11.*

Stubbings, J.A., 1973. Assessment of methods designed to reduce end-splitting during air-drying of debarked *E. grandis* poles. *Wattle Research Institute Report for 1972 - 73.*

Sweet, M., 1971. A bibliography of references to Eucalyptus. *Aust. Dept. of Agriculture. For. and Timber Bureau.*

Szasz, T., 1967. "Checking the causes of splitting and popping during the felling procedure and means of eliminating damage". *IUFRO proceedings, 14th Congress, Munich, Vol. 8, pp. 481 - 491.*

Tantichaiboriboon, V. and Cook, R.D., 1976. Effect of shape of cut on growth-stresses induced cracking in cut timber. *Report No. PB-251-364/AS, National Technical Information Service.*

Tantichaiboriboon, V. and Cook, R.D., 1977. Studies of effect of shape of cut on growth-stress induced cracking in cut timber. Part I: Three dimensional stress analysis. *Wood Science and Technology, Vol. 11, No. 3, pp. 237 - 247.*

Tantichaiboriboon, V. and Cook, R.D., 1977. Studies on effect of shape of cut on growth-stress induced cracking in cut timber. Part II: Optimization of axisymmetric cuts. *Wood Science and Technology, Vol, 11, No. 4, pp. 305 - 312.*

Tatishvili, E.M., 1957. Connection between physico-mechanical properties and characteristics of anatomical sructure of wood. *Akad. Wauk Armyanskoi SSR. Biol. i. Selkhoz. nauki Izvestiva 10, pp. 85 - 8. C.S.I.R.O., Australia. Translation, No. 4035 (1958).*

Taylor, F.W., 1968. Specific gravity differences within and among Yellow-Poplar trees. *Forest Products Journal, Vol. 18, No. 3, pp. 75 - 81.*

Taylor, F.W., 1973. Variations in the anatomical properties of South African grown *Eucalyptus grandis*. *Appita, Vol. 27, No. 3, pp. 171 - 184.*

Taylor, F.W., 1975. Fibre length measurement - an accurate inexpensive technique. *Tappi, Vol. 58, No. 12, pp. 126 - 127.*

Taylor, F.W. and Wooten, T.E., 1973. Wood property variation of Mississippi Delta Hardwoods. *Wood and Fibre, Vol. 5, No. 1, pp. 2 - 13.*

Thornthwaite, C.W. and Mather, J.R., 1957. Instructions and tables for computing potential evapotranspiration and the water balance. *Climatology, Vol. 10, No. 3, Centerton, New Jersey.*

Timell, T.E., 1969. The chemical composition of tension wood. *Svensk Papperstidning arg. 72, No. 6, pp. 173 - 181.*

Tischler, K., 1976. Improvement of *Eucalyptus camaldulensis* Dehnh. Wood. *Ph.D. Thesis, Hebrew University, Jerusalem.*

Tisseverasinghe, A.E.K., 1967. A preliminary report on the prevention of splitting in poles of *Eucalyptus grandis* using gang nails. *The Ceylon Forester, Vol. 8, No. 1 - 2, pp. 20 - 22.*

Trenard, Y. and Guéneau, P., 1975. Relations entre Contraintes de Croissance Longitudinales et Bois de Tension, dans le Hêtre (*Fagus sylvatica* L.). *Holzforschung, Bd. 29, H. 6, pp. 217 - 223.*

Turnbull, R.F., 1965. Review of current attitudes to growth stresses. *IUFRO (Section 41), Melbourne, Australia.*

United Nations Organisation, 1962. *Genetics of forest tree improvement.* Food and Agriculture Organisation of the United Nations, Rome. FAO Forestry and Forest Products Studies no. 16.

United Nations Organisation, 1976. Draft: *Eucalyptus for planting.* Food and Agriculture Organisation, June 1976.

Vaadia, Y.; Raney, F.C. and Hagan, R.M., 1961. Plant water deficits and physiological processes. *Annual Review of Plant Physiology, 12, pp. 265 - 292.*

Van der Westhuizen, P.K., 1978. Hardwood import replacement and improved utilization of locally grown hardwoods. *C.S.I.R. Special Report, Hout 152.*

Van Laar, A., 1961. *Eucalyptus saligna* in South Africa: An investigation into the silviculture and economics. *Annals of the University of Stellenbosch, Vol. 36, Series A, No. 1.*

Van Laar, A. and Bredenkamp, B., 1979. The effect of initial spacing on some growth parameters of *Eucalyptus grandis. South African Forestry Journal, No. 111, pp. 58 - 63.*

Van Vuuren, N.J.J.; Banks, C.H. and Stöhr, H.P., 1978. Shrinkage and density of timbers used in the Republic of South Africa. *Bulletin no. 57, Directorate of Forestry, Department of Environmental Affairs.*

Van Wyk, G., 1977. Progress with the *Eucalyptus grandis* breeding programme in the Republic of South Africa. *Third World Consultation on Forest Tree Breeding. Canberra, Australia.* Session 3: Population Improvement.

Van Wyk, G., 1980. The prospects of improving the inherent timber properties of *Eucalyptus saligna* by means of selective breeding. *Proceedings of Hardwood symposium, National Timber Research Institute, Pretoria, Republic of South Africa.*

Van Wyk, J.L., 1978. Hardwood sawnmilling can have a bright future in South Africa. *C.S.I.R. Special Report, Hout 162.*

Van Wyk, G. and Roeder, K.R., 1978. The status of tree breeding in South Africa. *South African Forestry Journal, No. 107, pp. 54 - 59.*

Vendhan, C.P. and Archer, R.R., 1977. Relief of growth stresses in diametrical planks. *Holzforschung, Bd. 31, H. 3, p. 90 - 96.*

Vermaak, G.S. and Quinn, P. 1982. Performance of South African grown and imported timber species as railway sleepers. *South African Forestry Journal, No. 122, pp. 39 - 48.*

Vurdu, H. and Bensend, D.W., 1979. Specific gravity and fibre length in European Black Alder Roots, Branches and Stems. *Wood Science, Vol. 12, No. 2, pp. 103 - 105.*

Wahlgren, H.E., 1957. Effect of tension wood in a leaning Eastern Cottonwood. *Forest Products Journal, Vol. 7, No. 6, pp. 214 - 219.*

Wardrop, A.B. and Dadswell, H.E., 1948. The nature of reaction wood. I. The structure and properties of tension wood. *Aust. Sci. Res., Series B. Biol. Sci., Vol. B1, No. 1, pp. 3 - 16.*

Wardrop, A.B., 1964. The reaction anatomy of arborescent Angiosperms. In: *Formation of Wood in Forest Trees.* Academic Press, Inc., New York, pp. 405 - 465.

Wardrop, A.B., 1971. Lignins, occurrence and formation. In: Sarkaren, K.V. and Ludwig, D.H. (Editors): *Lignins.* John Wiley and Sons, Inc., New York.

Watanabe, N., 1944. "On the internal stresses in tree stems. I. Internal stresses in tree stems of Sugi and Hinoki". *Journal of the Japanese Forestry Society, 26, pp. 104 - 111.*

Watanabe, N., 1965. A study of the origin oflongitudinal growth stresses in tree stems. *IUFRO (Section 41), Melbourne, Australia.*

Wattel Research Institute, 1972. *Handbook of Eucalypt growing.* Pietermaritzburg, Republic of South Africa.

Waugh, G., 1972. Growth stresses - genetic and environmental influences. *C.S.I.R.O., Forest Products Newsletter, No. 389, P. 3.*

Waugh, G., 1974. Controlling growth stresses. *Research working group of the Australian Forestry Council, Forest Genetics. Proceedings of the fourth meeting of representatives held at Melbourne, Victoria.*

Waugh, G., 1977. Reducing growth stresses in standing trees. *Australian Forest Research, Vol. 7l, No. 4, pp. 215 - 218.*

Wilhelmy, V., 1971. Residual stresses in wood and their effect on crack development. *Ph.D. Thesis, University of Wisconsin, Madison, U.S.A.*

Wilhelmy, V. and Kübler, H., 1973a. Probe for measurement of strains inside solid bodies. *Experimental mechanics, Vol. 13, No. 3, pp. 142 - 144.*

Wilhelmy, V. and Kübler, H., 1973b. Stresses and checks in log ends from relieved growth stresses. *Wood Science, Vol. 6, No. 2, pp. 136 - 142.*

Wilson, B.F. and Archer, R.R., 1977. Reaction wood: induction and mechanical action. *Ann. Rev. Plant Physiol., 28, pp. 23 - 43.*

Wood Southern Africa, 1984. Possible answer to Eucalypt splitting. *Wood Southern Africa, Vol. 9, No. 10, p.83.*

Yao, J., 1979. Relationship between height and growth stresses within and among White Ash, Water Oak, and Shagbark Hickory. *Wood Science, Vol. 11, No. 4, pp. 246 - 251.*

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APPENDIX ONE

METHODS FOR ASSESSING END-SPLITTING CAUSED BY GROWTH STRESSES AND THEIR RELIABILITY AS INDIRECT MEASURE OF STRESS LEVELS.

Introduction

Growth stresses cannot be measured directly but various techniques already exist which can be used to determine stress levels in the tree stem (see Nicholson, 1971a; Jacobs, 1938, 1939, 1945, 1965; Post, 1979; Beck, 1974; Sasaki *et al.*, 1981; Polge *et al.*, 1979; Post *et al.*, 1980; Wilhelmy *et al.*, 1973; Chardin *et al.*, 1983, etc.). These methods of stress assessment, though highly effective for certain purposes, i.e. studies on stress distribution in stems, are not readily suitable for rapid field assessment when large sample sizes are involved.

Certain stress characteristics can, however, be used to observe stress. Wood under tensile stress tends to contract when stress is released, while wood under compression stress tends to elongate. Within the elastic limit of the wood, this length change provides a reliable indirect measure of the level of growth stress in the tree.

In a standing tree a state of stress equilibrium exists between peripheral tensile and central compression stresses. Disturbances of this stress equilibrium, for instance by felling and cross-cutting the tree, results in the distortion of the component parts of the stem as they attain within themselves a new state of equilibrium (Waugh, 1972). This distortion manifests itself by the development of cracks and splits, mostly radial, in the cross-cut face of the log. Investigations have already proved that this stress characteristic can be used as a reasonably reliable measure of the stress level in that part of the tree stem despite the fact that the point of equilibrium will be strongly governed by the critical splitting value of the wood in that area of the stem (Nicholson, 1971b; Boyd, 1950 Part 1).

Methods of end-split assessment

(a) The girth increase technique

This technique has been applied for many years in South Africa to express log end-splitting. It concerned the measurement of the stem girth prior to cross-cutting, and again after 72 hours, and expressing the girth increase as a percentage of the original girth.

It was found that this percentage value is directly related to the proportional area occupied by splits on the cross-cut face (Malan, 1979a). Although the value obtained this way expresses the degree of log end-splitting reasonably well, the technique has several important shortcomings:

(i) It fails to measure splits not extending to the periphery of the cross-cut face.

(ii) Stem surface irregularities on the circumferential line near the cross-cut face where girth measurements are to be taken, can cause serious errors in the splitting values calculated, especially when low amounts of splitting occur.

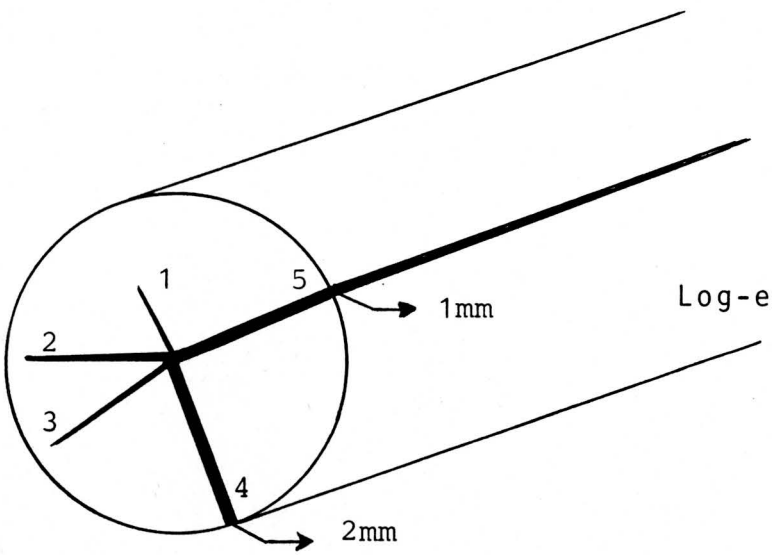
(iii) In order to increase the accuracy of the girth measurements, the position of the girth tape has to be marked off when the first girth reading is taken to enable the second reading to be taken on exactly the same circumferential line. Often, however, practical difficulties are experienced when this procedure is followed. For instance, log ends lying firmly on the plantation floor have to be either lifted, or the soil underneath removed, to enable the exact positioning of the girth tape on the marked circumferential line for the second reading.

(iv) The tearing out of wood material from the stem surface as a result of poor cross-cutting practices or other unavoidable causes, could render the first girth reading useless depending on the seriousness of the damage. Although this does not often occur, it could lead to the recording of many missing values in unfavourable site conditions i.e. on steep slopes or rocky sites.

(v) Since this technique requires the recording of two girth readings as well as a number of time consuming precautions to increase accuracy, i.e. the removal of the bark near the cross-cut surface, the marking of the circumferential position on the girth tape before cross-cutting, and the problems encountered with the second girth reading (point iii), a considerable amount of time and effort have to be spent in the plantation to collect reliable splitting data.

(b) The point scoring system

In order to overcome the shortcomings of the girth increase technique for split assessment, a point scoring system for assessing log end-splitting had been developed Conradie (1980). For splits not reaching the periphery of the cross cut surface, a score value of 0,5 is assigned for each half radius split length. For splits that do reach the periphery, a score value of 1 is added to the score for each one millimeter split opening at the periphery. The total score for each log end is adjusted by dividing it by 0,01 times the log end diameter (in millimeter) in order to obtain a score value for splitting proportional to the appropriate log end diameter. For example:



Log-end diameter = 200mm

Scores for individual splits:

Split 1	0,50
Split 2	0,75
Split 3	0,75
Split 4	3,00
Split 5	2,00

$$\text{Total splitting score (Adjusted)} = \frac{0,50 + 0,75 + 0,75 + 3,00 + 2,00}{200 \times 0,01}$$

$$= 3,50$$

Similar to the girth increases technique, the procedure also produces values (scores) for split log ends which are directly proportional to the proportion of the cross-cut face area occupied by splits (Conradie, 1980). This point scoring system also produces values that are well related to the surface strain, which occurred when stresses are released (Figure A1.1).

A direct relationship was found between peripheral split opening and the distance it extends along the longitudinal axis of the log (Conradie, 1980). Figure A1.2 serves a further illustration. It therefore means that the score value obtained for a particular log also serves as a reliable estimate of the average distance of split penetration along the longitudinal axis of the log.

Although the point scoring technique enables a fast and reasonable accurate assessment of log end-splitting without and direct measurements, split openings at the periphery have been measured by means of a venier caliper in this study to increase the accuracy of the split values obtained (Figure A1.3).

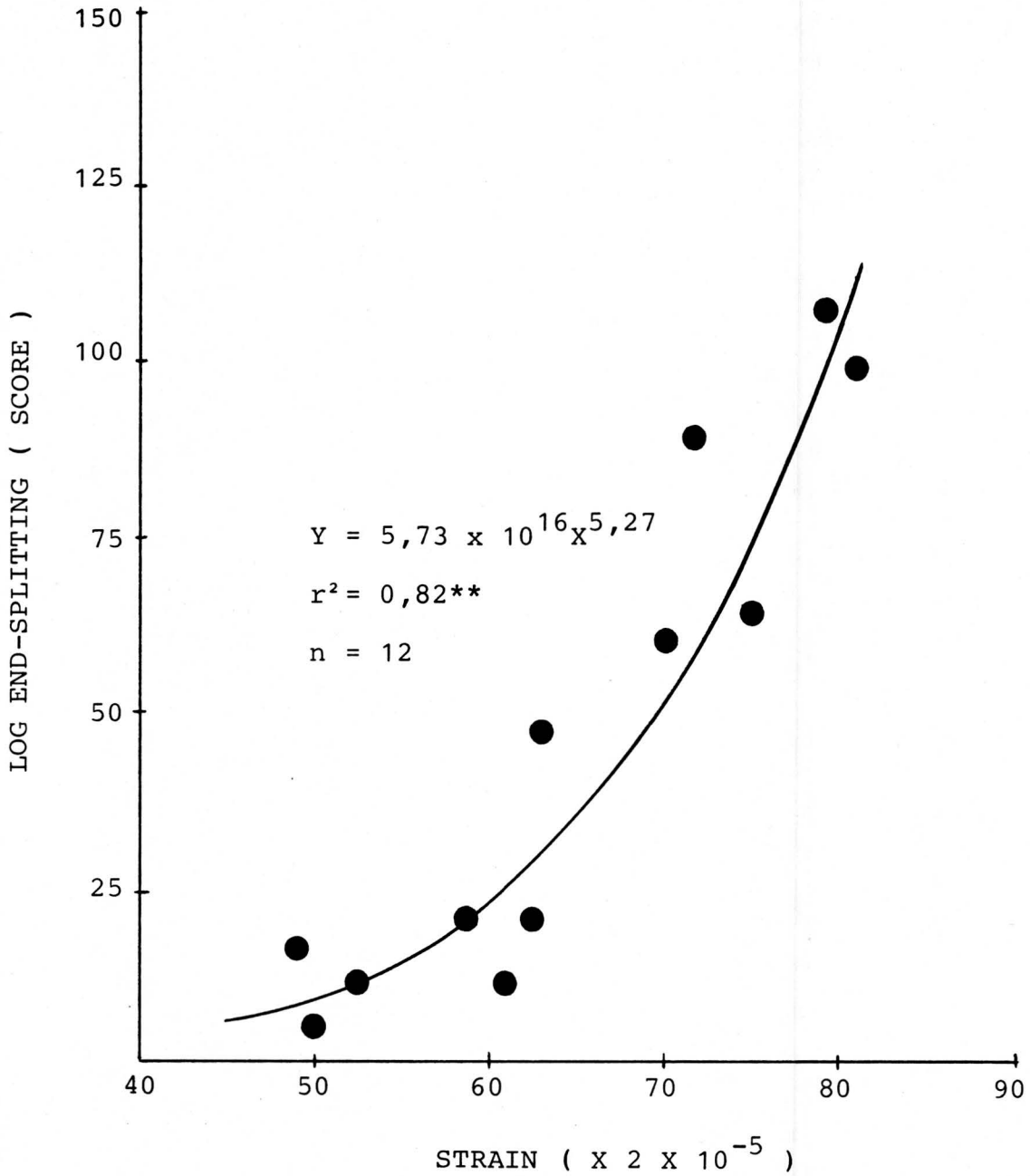


Figure A1.1:- Relationship between degree of log end-splitting and surface strain for South African *Eucalyptus grandis*.

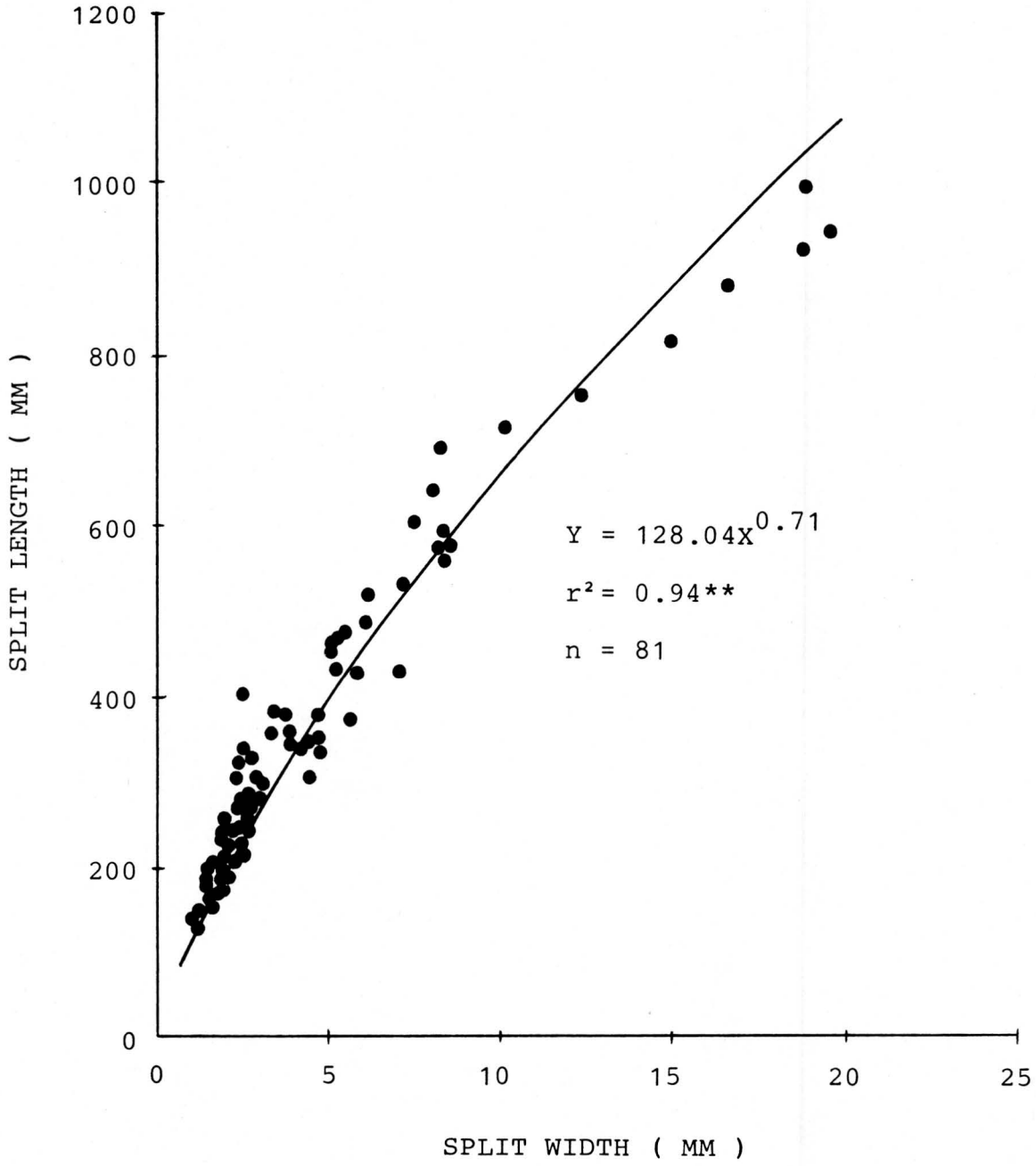


Figure A1.2:- Relationship between peripheral split width at the cross-cut face of the log and the split length on the surface.

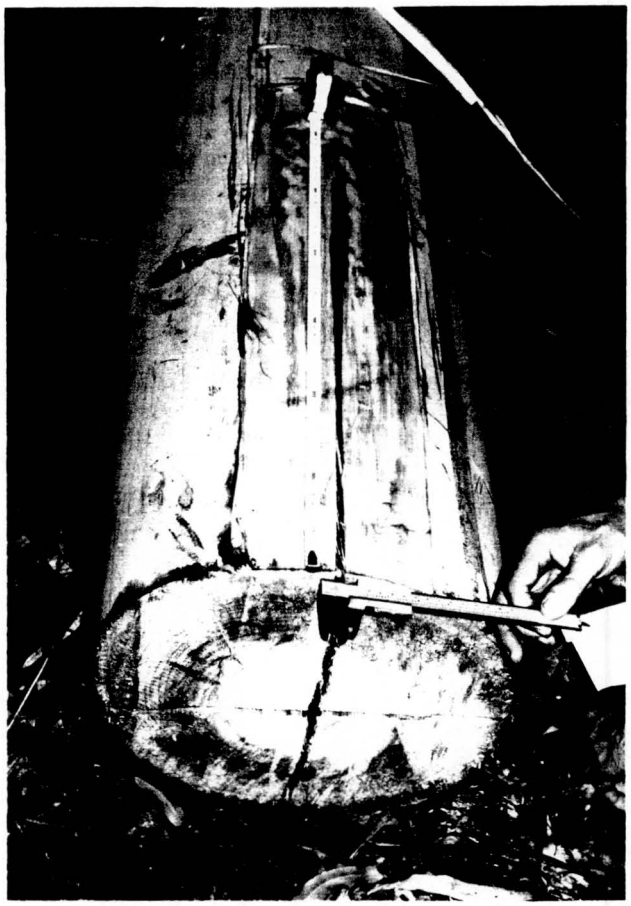


Figure A1.3:- Method used to measure peripheral split openings and its effect on split length on the stem surface.

APPENDIX TWO

DETERMINATION OF SAWN INDICES FOR *EUCALYPTUS GRANDIS* TREES SELECTED FOR BREEDING PURPOSES.

Until 1966 (G60), all selections were based on stem form and branch characteristics. Trees found to be acceptable in this respect, were subsequently felled and the logs converted into sawn boards at a local sawmill. After air seasoning the boards were visually assessed as regards splitting. Based on this, a rather subjective decision was made as regards the acceptability of a particular selected tree for breeding purposes. As already mentioned in Chapter seven, many of the trees rejected due to excessive splitting were retained in the breeding programme, and were progeny tested, mainly due to the otherwise outstanding properties of these trees, and also because of the lack of knowledge on the factors controlling growth stress levels.

Since 1966 a new system has been employed to screen selected trees as regards splitting. For this purpose a number of parameters were observed which would qualify the effect of growth stresses on total sawn yield and board dimensions. In order to determine species averages (splitting indices), for the various parameters, data collected from sawn material obtained from a large number of Eucalypt trees were analysed. Four indices were obtained quantifying splitting in seasoned sawn timber. The following minimum acceptance values for the four indices were adopted after the results of a number of selected trees became available (de Villiers).

(a) Unsplit Board length

The unsplit length of all full-length unedged boards sawn from a log expressed as a percentage of their total length.

Minimum acceptance value = 40 per cent

(b) Board width

The average trimmed board width expressed as a percentage of the log top diameter.

Minimum acceptance value = 28 per cent

(c) Board length

The average length of trimmed boards expressed as a percentage of the log length.

Minimum acceptance value = 76 per cent

(d) Sawn yield

The volume of all trimmed pieces (including a quarter of the volume of trimmed pieces shorter than 3,3m, but less than 1,2m long) expressed as a percentage of log volume.

Minimum acceptance value = 30 per cent

By calculating the weighted mean of the minimum acceptance values of the four indices, a single minimum acceptance value equal to 41,5 per cent has been obtained. Weighting was done in accordance to the economic importance of each index, using the following formula:

Weighted mean sawn index value =

((Index A) + (Index B) + (Index C - 2) + (Index D x 2))/4

Index D is extremely important as it is actually a combination of the other three indices. It is therefore multiplied by two. The value for index C, on the other hand, is too high in relation to the others and is therefore divided by two.

Since the adoption of this procedure, all Eucalyptus trees selected until recently, have been evaluated and screened with regards to splitting by means of this technique. A selected tree was accepted with regard to splitting, (a), if it met the minimum criteria set for all indices or, (b), if it failed in one of the criteria but produced values for the other three indices which were well above the genus average. In other words, yielded a weighted mean sawn index value equal to 41,5 or better.

As a rule the weighted mean sawn index value for Eucalyptus (41,5) was subtracted from the value calculated for a selected tree. Trees yielding positive values were accepted while those giving negative values were rejected.

Because of the good relationship found between log end-splitting and the four parameters mentioned earlier (Malan, 1979a), all selected trees felled from 1979 have been evaluated and screened as regards splitting by using only the degree of log end-splitting as selection parameter for growth stresses. This procedure reduced the time needed for growth stress assessment in selected trees considerably.

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